IMPACT OF PRODUCT LIFETIME
ON
LIFE CYCLE ASSESSMENT RESULTS

by

Can B. Aktas

B.S., Middle East Technical University, 2005

M.S., Middle East Technical University, 2007

Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2011

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This dissertation was presented

by

Can B. Aktas

It was defended on

March 16, 2011

and approved by

Dr. Kent Harries, Associate Professor, Department of Civil and Environmental Engineering

Dr. Amy Landis, Assistant Professor, Department of Civil and Environmental Engineering

Dr. Joe Marriott, Adjunct Faculty, Department of Civil and Environmental Engineering

Dissertation Director: Dr. Melissa M. Bilec, Assistant Professor, Department of Civil and Environmental Engineering

IMPACT OF PRODUCT LIFETIME ON LIFE CYCLE ASSESSMENT RESULTS

Can B. Aktas, Ph.D.

University of Pittsburgh, 2011

Global material consumption and related environmental impacts have exceeded the carrying capacity of many ecosystems by the end of the 20th century. The construction industry, being one of the most important industries for most nations, is responsible for a notable portion of materials consumption and environmental impacts.

Life cycle assessment (LCA) can be used to quantify environmental impacts of products and processes. However, many life cycle assessment studies do not adequately address the actual lifetime of buildings and building products. The goal of this research is to improve the LCA method and its results by quantifying the impact of lifetime on residential buildings and building products. Including accurate lifetime data into LCA allows a better understanding of a product's environmental impact and ultimately enhances the accuracy of LCA results.

Problems associated with lifetime are identified during a life cycle study for a natural fiber reinforced composite. The issue of lifetime was then investigated at a broader level in residential buildings and building products. The U.S. residential building lifetime as well as lifetime of commonly applied interior finishes has been refined to improve the accuracy of LCA results. Existing data on lifetime and product emissions were synthesized to form statistical distributions that were used instead of deterministic values. Results indicate that average residential building lifetime in the U.S. is currently 61 years and has a linearly increasing trend. Interior finishes on average constitute 3.9% and 7.6% of life cycle energy consumption for regular and low-energy homes, respectively. As use phase efficiency of residential buildings

improve, the relative importance of interior renovation over the life cycle of a residential building will increase.

Methods to estimate service life of building products have been investigated. A systematic, hybrid method for service life prediction that combines the effects of technical and social factors in a statistical approach was proposed. Example service life estimates were demonstrated for common residential interior finishes that are replaced frequently (i.e. at an interval less than the anticipated building life), and therefore require more maintenance planning and potentially have significant environmental impacts. The resulting lifetime estimation distributions have been presented for interior finishes.

Recommendations are made regarding strategies to reduce environmental impacts of interior finishes through reducing the disparity between design and actual lifetime. Existing environmental design strategies and policies have been reviewed, and specific suggestions for interior finishes are proposed. More specifically, the case for product differentiation by regionalization or by addressing the needs of different building types, and redesigning flooring overlays for disassembly and reuse was presented qualitatively.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

It is with great pleasure that I acknowledge individuals who have been crucial for completion of my Ph.D. First of all, I would like to thank my advisor Dr. Melissa Bilec for her generous support and insightful suggestions throughout my Ph.D. studies. It has been a privilege to work under her guidance.

I would like to express my gratitude to committee members Dr. Kent Harries, Dr. Amy Landis, and Dr. Joe Marriott. I was fortunate to have their suggestions that helped me to improve the quality of presented work.

I have been blessed with a family that has always been a source of love, inspiration, and encouragement to me. Their strong support enabled me to pursue my academic aspirations.

Last but not least, I would like to thank my wonderful wife Isil, for her constant support and patience. This would not have been possible without her.

GLOSSARY

ASTM – American Society for Testing and Materials

BEES – Building for Environmental and Economic Sustainability

CO_2e – Carbon Dioxide Equivalent

GFRC – Glass fiber reinforced composite

GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

ISO – International Organization for Standardization

LCA – Life cycle assessment

LCI – Life cycle inventory

LCIA – Life cycle impact assessment

LDPE – Low Density Polyethylene

NFRC – Natural fiber reinforced composite

NIST – National Institute of Standards and Technology

TRACI – Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

UV – Ultraviolet

1.0 INTRODUCTION

With increasing awareness of consumer's environmental concerns, a new market for 'green' products is rapidly emerging. However, there needs to be a viable method to evaluate environmental performance of such products. Life cycle assessment (LCA) is a tool that can be used to quantify the environmental upstream and downstream impacts of a product or process. Background information and a description of the LCA method is presented in Chapter 2.

A pultruded natural fiber reinforced composite that has potential applications as a building product was analyzed from a life cycle perspective. The novel aspect of this research was the pultrusion of a natural fiber together with a bio-resin. Although natural fibers have been incorporated in composites previously, pultrusion is one of the least energy-consuming production methods and therefore the new composite has the potential to become an environmentally friendly building product. Chapter 3 presents a detailed description of this study together with important outcomes.

Problems with product lifetime were identified during the life cycle study for a natural fiber reinforced composite. Lack of research on actual lifetime of buildings and building products led to further investigation of product lifetimes and the existing practice of arbitrarily choosing lifetime for building products in LCA. The research that followed was aimed towards improving the accuracy of building LCA studies. Product examples were chosen from residential interior finishes due to their frequent replacement over the life cycle of a building.

The research was centered around three main components: quantifying the impacts of product lifetime on a residential model, proposing a method to estimate service life of building products, and strategies to modify product lifetime based on consumer needs. Using revised product lifetime in a residential model demonstrated the potential degree of error introduced into a building LCA study by excluding or using arbitrary lifetime data. A method that can accurately predict product lifetime by including technical factors as well as the effects of social factors was developed due to their strong influence on product lifetime and related emissions. Design strategies that can be applied to interior finishes to reduce the disparity between design and service life was also described together with examples. Each of these topics has been covered in depth in Chapters 4 to 6.

Conclusions from the study with regards to each research question were presented in Chapter 7. Recommendations for future studies that could build on this work are also described.

1.1 MOTIVATION

Many LCA studies do not adequately address the actual lifetime of buildings and building products, but rather assume a typical value. However, assuming a generic timeframe is not adequate if the assumed lifetime values are chosen based on design conditions rather than actual life situations. The actual lifetime of a product may depend on many factors other than technical requirements, resulting in a significant difference between the actual lifetime and the design lifetime used in the assessment. The importance of actual lifetime is magnified when comparing alternate products for the same application, or in situations where the product being studied is a subset of a larger system that is being analyzed, as in the case of buildings. The main focus of this research was on quantifying the impact of product lifetime on LCA results.

During product lifetime research, it was found that existing service life prediction methods do not incorporate the effects of social factors into analysis. Although product failure caused by lack of durability is important, product obsolescence dependent on user or occupant "taste" also plays a crucial role in the product replacement decision and may even be more important than technical durability for certain product categories. The identified gap in existing state-of-practice in service life prediction led to the development of a new, hybrid method that considers the effects of consumer behavior in addition to technical durability. Service life estimates calculated by this method can be directly incorporated into LCA studies to improve accuracy of results.

The disparity between design and actual lifetime of a product signifies that either the product is discarded and replaced by a newer model while it was still functioning, or the product is being used after its intended or design use period. Both cases indicate that there is a disagreement between consumer desires and opinions, and what the manufacturer is producing. Applicable policies and environmental design strategies aiming to decrease this disparity were also a motivation for this study.

1.2 RESEARCH CONTEXT AND CONTRIBUTION

The goal of this research is to determine the impact of the selection of lifetime parameters on LCA results and make suggestions to improve the LCA method. To this end, the impact of lifetime on LCA results has been demonstrated for residential buildings by using interior finishes as a case study. The amount of potential error introduced into the study by disregarding lifetime data is also provided. Another research outcome is to provide reliable data on actual use periods of several interior finishes by taking into account the effects of social factors as well as design lifetime. The context in which the terms ‘social factors’ and ‘consumer behavior’ were used in the manuscript was to describe additional factors that affect lifetime of buildings and building products other than strength or durability.

Average residential building lifetime presented in this study provides accurate data regarding the existing trends in the U.S. Including lifetime information into LCA allows a better understanding of the life cycle impacts, ultimately enhancing the accuracy of LCA studies.

U.S. average practices are used to define the residential model, and the residential building lifetime used in the study. The construction industry is moving toward increased efficiency and reduced environmental impacts. This progression can be observed from the rapid increase in the number of green products and number of low-energy buildings that are being built. A distinction has been made between regular residential buildings and low-energy buildings to quantify impacts of lifetime in a broader context.

Service life prediction methods have been reviewed to determine their viability for interior finishes. Existing methods approach the problem from a purely technical point of view, and so are limited in scope and application. A hybrid method based on statistical analysis of data is developed to determine service life of building products that can be used within LCA. A reliable service life prediction method would have direct applications in future LCAs and would be an important step toward improving the existing state-of-practice. In addition, facility and asset managers would benefit from a greater ability to foresee and plan for future expenditures, and for economic decision-making to make informed decisions on investment planning. The developed method is supported by examples for interior finishes, but is equally applicable to other products that are studied within LCA.

Another contribution of this research was to identify possible strategies that can be applied either by legislative bodies or by manufacturers, that aim to reduce the difference between actual and design lifetimes of interior finishes. Proposed changes would contribute to the efficient use of materials and reduce environmental impacts of products simultaneously. The economic bottom-line is also addressed in the proposed strategies to facilitate manufacturers to implement design changes voluntarily.

1.3 RESEARCH QUESTIONS

Questions that were investigated in this dissertation are as follows:

1. What is the environmental performance of a natural fiber reinforced composite over its life cycle in comparison to a glass fiber reinforced composite? What is the impact of product lifetime on these results?

2. What is the impact of product lifetimes on residential building LCA results? How do LCA results vary based on improved lifetimes?

3. Are there predictive methods that can estimate the lifetime of a product by including consumer behavior as a parameter? Can predictive methods provide reliable estimates for lifetime?

4. What strategies can be developed to decrease the disparity between design and actual lifetimes?

2.0 BACKGROUND ON LIFE CYCLE ASSESSMENT

LCA is a systematic method that quantifies emissions and environmental impacts of products or processes over their life cycle. Product LCA commonly starts from raw material acquisition and includes production, transportation, use and end-of-life phases. Analyzing products over their life cycle enables decision makers to understand the true environmental impacts of their selections.

Some early examples of LCA were conducted during the late 1960s and early 1970s, with two notable studies conducted for The Coca Cola Company and Mobil Corporation (Curran 1996; Tan and Culaba 2002). Early studies focused more on direct material inputs, energy consumption, and waste output. Following the oil shortages in 1970s, many countries started using energy analysis as a way to investigate the feasibility of new fuel substitutes, especially bioethanols. After the oil crisis faded, interest in such studies declined and activity in the U.S. on environmental LCAs continued at a slow pace of around two or three studies per year. The exact number is not known for certain since most studies were performed for private clients and not released to the public (Tan and Culaba 2002; Koo 2006). LCA standards and definitions started to develop during the 1990s in various European countries culminating in a set of standards, ISO 14040-14044, a guideline for LCA studies (ISO 2006), as a subset of ISO 14000 Environmental Management Systems.

An LCA is comprised of four different stages: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and improvement and interpretation. The goal and scope of a study describes the intended use of the analysis, boundary, functional unit and other items (including temporal aspects). Inventory analysis or LCI involves performing a thorough data collection that quantifies the material, energy, and emissions that occur over the life cycle for the selected functional unit. LCIA expresses the LCI data in terms of environmental impacts. The LCI data is classified into impact categories, such as global warming potential, ecotoxicity, or eutrophication. The interpretation and improvement analysis stage is where conclusions and recommendations are expressed with regards to the goal and scope definition (ISO 2006). All phases are iterative and feedback loops often occur as shown in Figure 1.

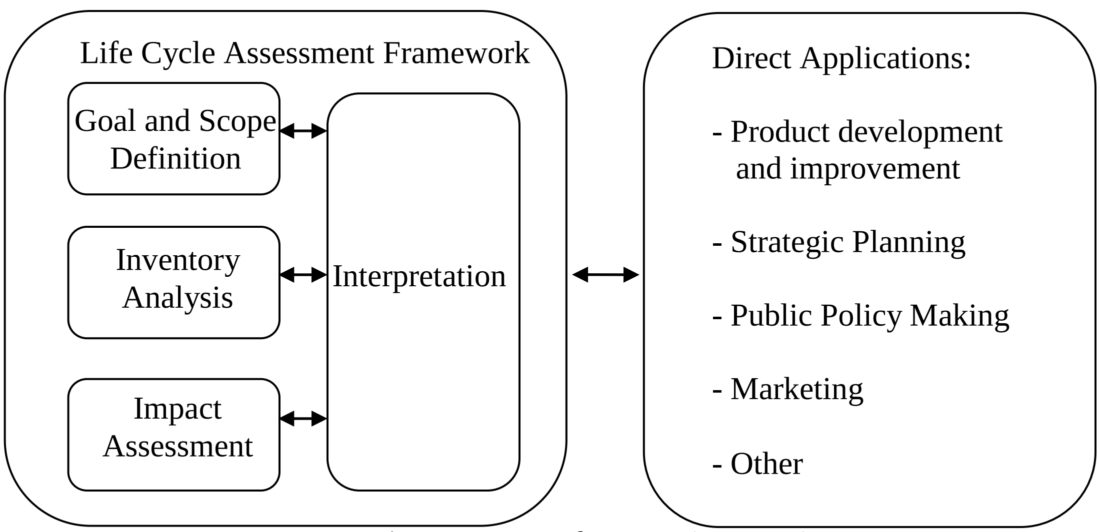


Figure 1. Stages of an LCA (ISO 2006)

Use of LCA offers the possibility of identifying weak points over the life cycle of products and suggests improvements for environmental performance. Governmental institutions, private firms, consumer organizations, and environmental groups use LCA as a decision support tool. The scope of decisions covered by LCA ranges from broad policy changes to specific product or process selection (ISO 2006).

2.1 UTILIZED LCA TOOLS

Numerous databases and tools exist in order to aid LCA researchers and practitioners. Such tools were used extensively for applicable products during data collection in this research.

Databases that contain LCI information for various products are available for LCA practitioners. Programs that allow access to these databases also have the ability to calculate product impact assessment. Based on a survey conducted among LCA practitioners, 69% of respondents reported to be using off-the-shelf LCA programs for their research (Cooper 2006). For example, Ecoinvent v2 and ETH-ESU LCI databases incorporated in the Simapro v7.1 program (SimaPro) were used for data on environmental impacts of building interior finishes. Traci 2 v3.01 (Bare 2003) was used for impact assessment of inventory data.

Building for Environmental and Economic Sustainability (BEES) version 4.0 that was developed by the National Institute of Standards and Technology (NIST) was another program used extensively during the study. BEES include both economic and environmental performance data for 230 building products. Economic factors can be included into the study by adjusting the respective weight between environmental and economic impacts. The model uses a life cycle approach to calculate product impacts (Lippiatt 1999; Lippiatt 2001; Lippiatt 2007; Lippiatt 2008).

2.2 SHORTCOMINGS OF LCA

LCA is a powerful tool for environmental impact assessment of products and processes. However, there are several shortcomings of the method that have been pointed out by various researchers. For process based LCA, there are problems with defining the system boundary. The variety of possible boundaries to be selected, even by adhering to the ISO 14040 standards on LCA, introduces subjectivity into the analysis and provides some control of the end result by the analyst (Suh 2002; Korhonen 2005; Bilec 2006; Huppes 2006; Mungkung 2006; Bilec 2007; Davis 2007; Kofoworola 2008). Not reporting the underlying assumptions and values as well as the use of data from unreliable sources that cannot be validated was noted by several researchers as another problematic area (Ayres 1995; Dahllof 2004; Bilec 2006; Mungkung 2006; Reap 2006; Bilec 2007; Davis 2007; Kofoworola 2008). Although ISO 14040 recommends avoiding allocation whenever possible, its application in situations where it is strictly necessary can further add to the problem (Dahllof 2004).

Another topic that draws criticism in LCA is the low spatial resolution of results (Bare 2003; Dahllof 2004; Udo de Haes 2004; Guinee 2006; Reap 2006; Teixeira 2006; Udo de Haes 2007). LCA is considered to be a global tool. This could be considered as one of its strengths as well as its weakness. The impacts are tied only to the product function and not specifically to where the impacts occur, making it site-independent (Ness 2007). In general the analysis is performed at a global level without a special focus on environmental impacts at the regional or community level (Kijak 2004; Schianetz 2007).

An ideal process based LCA without budget or time constraints would use highly reliable data and would include all life-cycle stages. Unfortunately, completing comprehensive assessments at a high level of depth and sophistication would require impossibly large amounts of time, data and resources. Therefore, every study must be limited in some aspect of comprehensiveness. There is a certain trade-off between depth and comprehension versus feasibility (Bare 2003; Ny 2006).

3.0 LIFE CYCLE ENERGY CONSUMPTION OF PULTRUDED FLAX FIBER AND GLASS FIBER REINFORCED COMPOSITES

3.1 INTRODUCTION

Composites, especially fiber reinforced composites have developed rapidly in the past 40 years and are now commonly used in the construction and auto industries (Umair 2006). Natural fibers have been used throughout history and may be considered to be one of the first engineering materials humans ever used (Fernandez 2006). Due to their low production energy, proposed ability to sequester carbon over their life cycle, low weight, and degradability, the use of natural fibers are increasing rapidly in response to market demands for ‘green’ products. Switching from glass fiber reinforcement to natural fiber reinforcement reduces environmental impacts of a given composite (Schmidt and Beyer 1998; Wotzel, Wirth et al. 1999; Hansen, Flake et al. 2000; Pervaiz and Sain 2003; Joshi, Drzal et al. 2004; Schmehl, Müssig et al. 2008).

Life cycle energy consumption of pultruded natural fiber reinforced composites (NFRC) made of bio-resin and flax fibers was compared to a E-glass fiber reinforced composite (GFRC) consisting of polyester resin. The reduction in energy consumption of flax fiber reinforced composites was quantified while important points that should be considered in future similar studies were identified. This research was performed collaboratively with a major pultruded composite manufacturer. While green composites have application areas in many sectors, this product is unique because it is one of the first pultruded green composites that would be used to manufacture various building products.

Background information on important products and processes necessary for composites were presented, along with data points obtained through literature and the manufacturing company. Assumptions have been explained in detail with supporting arguments. Discussion of results highlights important outcomes of the study. The conclusions section provides a concise overview of important findings as well as suggesting improvements and identifying areas that require further research.

3.2 BACKGROUND

This background section includes information on flax and glass fibers, followed by information on the polymeric matrix and production processes for composites.

3.2.1 Flax fibers

Commercially, natural fibrous materials are predominantly used in the automotive industry. Their use in the German automotive industry alone has surpassed 19,000 tons based on 2005 data, of which flax fibers constitute close to 65% (Miao and Finn 2008). By substituting 50% of glass fiber reinforced composites with natural fiber reinforced composites in North American auto applications, an estimated 3 million tons of CO_2 emissions and 1.2 million m^3 of crude oil can be saved (Pervaiz and Sain 2003).

Cultivation of natural fibers amounted to 5 million tons globally in 2001. Flax fibers have a large share in the overall natural fiber industry. Although global production of flax exceeds 12 million acres, 418,000 acres of land were planted in the U.S. in 2010 (Fernandez 2006; USDA 2010). The majority of production in U.S. comes from North Dakota (96% of U.S. flax cultivation) followed by South Dakota, Montana and Minnesota (USDA 2010). As a comparison, 800,000 acres of flax was planted in the year 2005 in Saskatchewan, which is a northern neighbor of North Dakota (Tripathy 2009). Flax farming in the U.S. is mostly for linseed, requiring other products of the flax plant to be imported. About $150 million of flax fiber, flax-containing yarn and flax fabric were imported in the year 2000; an estimated value of $500 million in finished products (Durham 2000).

Flax may be cultivated to obtain three distinct agricultural products: the seed, linseed oil and fiber. However, these three products cannot be optimally obtained from the same cultivating process or harvesting schedule. The fiber obtained from plants cultivated for seeds has a significantly decreased tensile strength (Fernandez 2006).

Since flax fibers are obtained from a natural plant, it is inevitable that there be variations in the properties of fibers. These variations have been brought up by researchers as issues associated with the use of natural fibers (van de Velde 2001a; van de Velde 2001b; Bismarck 2002; Bos 2004; Bos 2006; Stuart 2006; Santulli and Caruso 2009). Tensile strength and modulus of elasticity are some mechanical properties where variations can easily be observed. Local soil, water, and climatic conditions affect both crop output and fiber properties on a yearly basis.

Environmental impacts of flax cultivation differs by region; energy consumption and emissions of a crop cultivated in a developed country could differ by at least an order of magnitude when compared to a similar crop cultivated in a region which does not use machinery or chemicals. This difference mainly results from the disparate use of fossil fuels and fertilizers (Hansen, Flake et al. 2000; Joshi, Drzal et al. 2004).

Woven flax fibers, or linen, were used in the pultrusion process instead of individual fiber tows or chopped fiber mats. This method was preferred over inclusion of individual fibers distributed randomly among the polymeric resin matrix both due to its improved technical properties and also due to improved aesthetic qualities. By adjusting the number of fibers that go into making the rovings, the thickness, and density of the fabric could be modified. Although the density of individual flax fibers is given as 1.4-1.5 g/cm^3 (Joshi, Drzal et al. 2004; van Dam 2004; Miao and Finn 2008), the areal density of fabric used was lower due to voids of a woven fabric. A sample of this fabric is shown in Figure 2.

Figure 2. Texture of linen sample used in the study

3.2.2 Glass Fibers

Glass fibers are one of the most widely used reinforcements in the composite industry owing to their high tensile strength. Glass fibers are mainly composed of silica but contain impurities to lower working temperatures. As part of the manufacturing process, newly formed fibers, having a diameter of 5-25 μm, are passed through a light water spray followed by application of a protective binder. Individual fibers are not preferred in composite manufacturing, but rather are used in the form of strands which usually consists of around 200 filaments (Agarwal 1990; Pervaiz and Sain 2003).

Compared to natural fibers, glass fibers are more consistent in terms of density, strength, and geometric dimensions. The partnering pultrusion company gave the density of E-glass fibers as 2.57 g/cm^3, which was consistent with existing literature. Depending on the intended use, tensile strength of glass fibers could vary from 2,000 to 3,500 MPa, although Young's modulus tend to be relatively constant, 70-76 GPa (van Dam 2004; Miao and Finn 2008).

3.2.3 Polymeric Matrix

One of the major constituents of composites is resin, which is usually grouped into two categories: thermoplastics and thermosets. A thermoplastic resin melts when heated and solidifies when cooled. The long chains of polymers do not form a strong covalent bond. Theoretically, the heating and cooling cycle can be repeated many times without the loss of specific properties, but in practice there is a limited number of cycles that the resin can undergo before it becomes undesirable for structural application (Koo 2006). Conversely, a thermoset resin will harden permanently by irreversible cross-linking at elevated temperatures and will retain its shape during subsequent cooling and heating cycles. This characteristic makes thermoset resin composites desirable for structural applications (Umair 2006). The most common resins used in composites are epoxies, vinyl esters, and unsaturated polyesters.

In the U.S., unsaturated polyesters amount to approximately 75% of all polyester resins used. The advantages of unsaturated polyesters are their dimensional stability and low cost as well as ease of handling, processing, and fabricating. They have excellent durability and can be used with fire retardants. However, they are sensitive to light and ultraviolet (UV) radiation (Umair 2006).

Since resins make up a large portion of expenses in composites, filler materials are used to replace a portion of resins. Filler material may also improve composite properties such as fire and chemical resistance, mechanical strength, and improved shrinkage, fatigue, and creep resistance. UV inhibitors are one of the most common and important additives as they decrease the harmful effects of UV radiation.

Bio-resins are slowly gaining ground in the composite industry with increasing environmental awareness and product demand. With major technological shift in some of the world's largest chemical companies from traditional petrochemical processing to agricultural biotechnology, biopolymers are soon expected to compete with various plastics (Mohanty, Misra et al. 2005).

The two composites investigated were distinctly different in terms of composition. The reference product was made of traditional materials: glass fibers as reinforcement and polyester as the binder resin used in pultruded glass fiber reinforced composites. The natural fiber reinforced composite was made of linen as the reinforcement and a bio-resin as the binder matrix. In order for this new composite to perform satisfactorily for mechanical strength, a small amount of glass fiber strands were included to assist in the pultrusion process.

3.2.4 Production Techniques

Several techniques have been developed to produce fiber-reinforced composites. Fabrication techniques suitable for manufacturing natural fiber reinforced composites include the hand layup method for unidirectional fibers or for fabrics, sheet molding for short or chopped fibers, filament winding and pultrusion for continuous fibers or fabrics (Mohanty, Misra et al. 2005). There is significant difference in the energy requirements of these techniques. Composite production by hand layup, which is one of the most energy intensive processes, is reported to consume 19.2 MJ/kg, whereas resin transfer molding, vacuum assisted resin infusion or cold press methods require around 10-13 MJ/kg. Pultrusion is reported as one of the least energy consuming processes, requiring 3.1 MJ/kg (Suzuki 2005; Song, Youn et al. 2009). A comparison among different production techniques was not performed. The goal was to compare alternative pultruded composites.

In the pultrusion process, fibers mixed with the resin are drawn through a die (or dies) shaping the composite that are cured using an in-line heating system and then cut to length all in a continuous process. Continuous profiles of any dimension can be produced quickly and efficiently with the pultrusion method (Fernandez 2006). Putruded products are largely restricted to having longitudinally oriented fibers and randomly oriented chopped fiber mat (scrim) composition. Machinery used to pultrude flax fiber reinforced composites was the same as glass fiber reinforced composites and no problems were reported related to the use of flax fibers with the bio-resin.

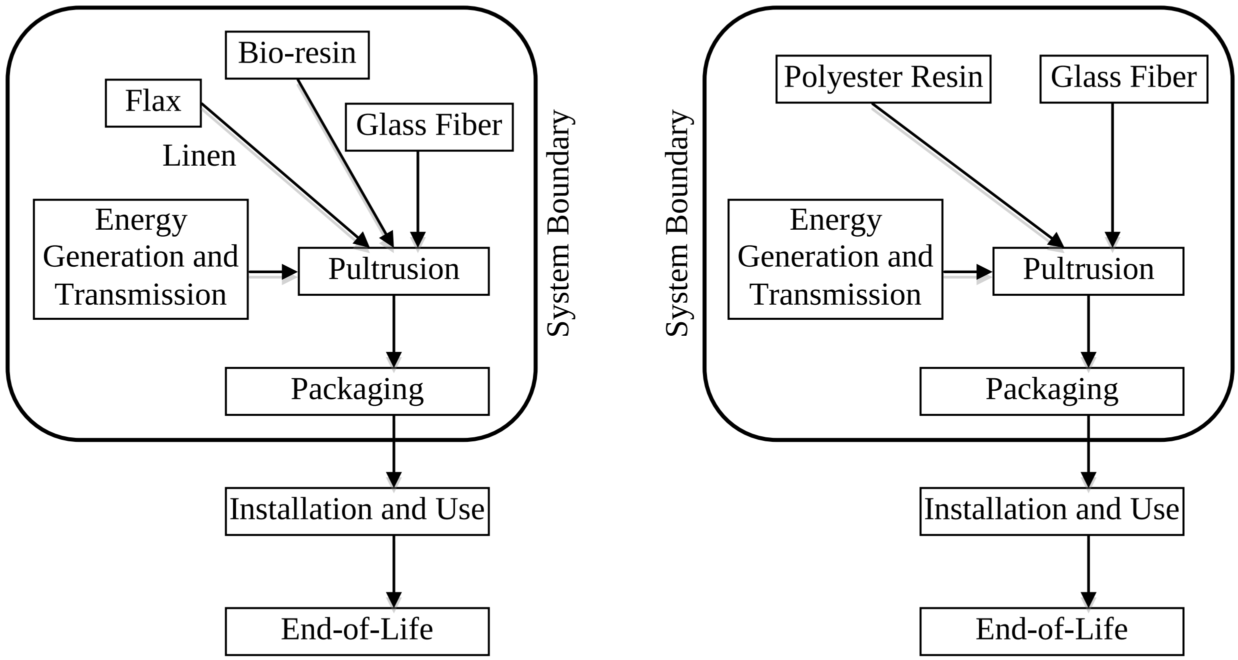
3.3 CUMULATIVE ENERGY BALANCE

3.3.1 Functional Unit

The functional unit used for comparison was 1 cm^3 of pultruded composite. The potential applications of flax fiber composites are numerous and so the functional unit was chosen so as to allow easy application of results to different products with known volumes. Pultruded NFRCs were not intended for use as structural members or under mechanically demanding conditions and so a comparison based on a functional unit of equivalent strength or stiffness was not necessary. A supporting fact was that several published studies also used volume as a functional unit when analyzing natural fibers (Schmidt and Beyer 1998; Wotzel, Wirth et al. 1999; Joshi, Drzal et al. 2004; Schmehl, Müssig et al. 2008; Thamae 2008). As for the temporal aspect, the manufacturer stated that the expected lifetime of composite alternatives were the same. Since the natural fiber reinforced composite was a newly developed product, lifetime data was not available through literature. Therefore, lifetime of alternatives was assumed to be equal during initial calculations. However, a sensitivity analysis was conducted to determine the effect of lifetime on calculated results.

3.3.2 System Boundaries

Process flow diagrams and system boundaries used to calculate embodied energy of flax fiber and glass fiber reinforced pultruded composites are shown in Figure 3. Transportation of materials and products, which is commonly inherent in every process was not explicitly shown but was included in the system boundaries. Material inputs and energy consumption of different processes in different locations were included in the analysis to model life cycle impacts.



A. Flax Fiber Reinforced Composite B. Glass Fiber Reinforced Composite

Figure 3. System boundary used for composites (a) Flax Fiber Reinforced Composite (b) Glass Fiber Reinforced Composite

Note: Although not shown explicitly, transportation is included in the system boundary.

Since equal lifetime was assumed for composite alternatives as described in Chapter 3.3.1, use phase energy consumption of composite alternatives would also be equal unless being used for thermal insulation, which was not one of the intended products during the study. For automobile applications, the use phase of composites becomes the dominating life cycle phase because additional weight of a composite increases fuel consumption over the life cycle of the composite or the automobile. However, flax fiber composites were intended to be used as building products (e.g. railings) and therefore the use phase does not result in differences in emissions among composite alternatives. Similarly, no significant difference was expected for the installation phase energy consumption of composite alternatives.

Published values for end-of-life impacts of natural fiber reinforced composites were estimated to be around 0.1% of the overall life cycle energy consumption of a composite (Thamae 2008). Since this value constitutes a minimal portion of life cycle impacts, end-of-life phase of composites were excluded.

3.3.3 Embodied energy of raw materials

Life cycle energy consumption of pultruded glass fiber reinforced composites was compared to pultruded natural fiber reinforced composites. Different phases over the life cycle of composites were included, such as raw materials extraction and processing, transportation, manufacturing, and packaging. Embodied energy was also included into the analysis at all phases considered.

Glass fibers together with polyester accounted for the majority of components in GFRC, whereas linen with bio-resin, together with minute amounts of glass fiber strands were the main constituents of NFRCs. Glass fibers made up approximately 50% of GFRC. Glass fibers present in the NFRC were located at the center section of the composite, covered over by linen on both sides. Their use was deemed necessary during pultrusion in order to improve mechanical properties of the composite and to aid the pultrusion process.

Reported energy consumption of flax cultivation varies from 2.6 to 4.0 MJ/kg (Hansen, Flake et al. 2000; Joshi, Drzal et al. 2004; Schmidt, Jensen et al. 2004). An additional 5.6 MJ/kg of energy was required to extract fibers from the plant after harvesting and to weave them into linen (Joshi, Drzal et al. 2004). A life cycle energy consumption of 9.6 MJ/kg was used in this study for production of linen including upstream processes (Joshi, Drzal et al. 2004).

Production of glass fibers is an energy intensive process. The energy consumption of glass fibers was taken as 48.3 MJ/kg. Specific gravity of glass fibers were taken as 2.6 g/cm^3 (Joshi, Drzal et al. 2004).

The life cycle energy consumption of polyesters ranged between 49.0-64.5 MJ/kg (Dhingra, Overly et al. 2001; Patel 2003; Suzuki 2005). The mean value of 58.8 MJ/kg was used. Reported density of polyester was between 1.1-1.5 g/cm^3 (van Dam 2004; Mohanty, Misra et al. 2005; Patnaik 2009), where 1.4 g/cm^3 was used in this study.

A multi-purpose bio-resin “Envirez 70301” obtained from Ashland Inc. was used to produce NFRCs. This medium viscosity resin was suitable for use in the pultrusion process and has a clear color that makes the end product visually appealing. This specific bio-resin has a styrene content of 30% and a bio-content of 22%. Due to confidentiality reasons, a complete list of ingredients and their distributions were not available. The energy consumption of this bio-resin was 49.9 MJ/kg, which is 8.9 MJ/kg lower than polyester (Moffit 2009). The density of the multi-purpose bio-resin was reported to be 1.4 g/cm^3 by Ashland (Moffit 2009).

3.3.4 Composite specific gravity and constituent ratios

The relative proportion of constituents has a profound impact on the properties of composites. Proportions can be found either as weight fractions or volume fractions depending on the calculation method. Weight fractions are more suited towards experimental methods. Volume fractions are more commonly used during theoretical analysis of a composite (Agarwal 1990). Experimental data combined with composite volume and weight laws were used to calculate the density of composites.

The majority of a GFRC is formed by combining polyester and glass fibers; the distribution being close to 50% polyester and 50% glass fiber by volume. Other ingredients of the composite are either used in minute amounts, or their production is not significantly different than polyester or glass fibers and therefore can be combined when calculating energy consumption. The resulting composite density was calculated to be 2.0 g/cm^3 as shown in Table 1, which was verified with the pultrusion company and was reported to be within their expected range.

Table 1. Glass Fiber Reinforced Composite – Mass and Volume Constituents

	d_i (g/cm^3)	W_i (%)	Mass (g)	Volume Ratio (%)
Polyester	1.4	35	0.7	50
Glass Fiber	2.57	65	1.3	50
GFRC	2.0	100	2.0	100

NFRC densities were calculated using Equation 1 based on individual material inputs and densities. Two different linen fabrics weighing 225 g/m^2 and 685 g/m^2, denoted as NFRC I and NFRC II respectively, were chosen by the pultrusion company. Bulk density was 0.69 g/cm^3 and 0.90 g/cm^3 for 225 g/m^2 and 685 g/m^2 type linen, respectively. Table 2 and Table 3 present mass and volume ratios for NFRC I and NFRC II.

$$d_c = \frac{1}{\sum_{i=1}^{n} \left(W_i / d_i \right)} \qquad \textbf{Equation 1.}$$

where d_c is the density of the composite (g/cm^3), W_i is the percent weight of each constituent in the composite (%), d_i is the density of each constituent in the composite (g/cm^3), and n is the number of constituents that are present in the composite.

Table 2. Natural Fiber Reinforced Composite I (NFRC I) – Mass and Volume Constituents

	d_i (g/cm^3)	W_i (%)	Mass (g)	Volume Ratio (%)
Flax Fabric	0.69	30	0.33	49
Bio-Resin	1.36	53	0.60	44
Glass Fiber	2.57	17	0.19	7
NFRC I	1.13	100	1.13	100

Table 3. Natural Fiber Reinforced Composite II (NFRC II) – Mass and Volume Constituents

	d_i (g/cm^3)	W_i (%)	Mass (g)	Volume Ratio (%)
Flax Fabric	0.90	43	0.51	57
Bio-Resin	1.36	41	0.48	35
Glass Fiber	2.57	16	0.20	8
NFRC II	1.19	100	1.19	100

Densities of NFRC I and NFRC II were calculated to be 1.13 g/cm^3 and 1.19 g/cm^3 respectively. Test results and measurements on specimens were used to verify the density of both composites.

3.3.5 Life cycle phases

Life cycle energy calculations of composites have been separated according to different phases in this section. Results are presented together with underlying assumptions. Additional calculation details can be found in the Appendix.

3.3.5.1 Raw Materials

Raw materials energy consumption was calculated by multiplying the production energy of each component by their respective mass distribution in the composite. Table 4 presents total energy consumption of raw materials for each composite.

Table 4. Total raw material energy consumption of composites (Hansen, Flake et al. 2000; Dhingra, Overly et al. 2001; Patel 2003; Joshi, Drzal et al. 2004; Schmidt, Jensen et al. 2004; Suzuki 2005; Moffit 2009)

Energy Consumption of Raw Materials	Production Energy (MJ/kg)	GFRC (kJ/cm^3)	NFRC I (kJ/cm^3)	NFRC II (kJ/cm^3)
Glass Fiber/Roves	48.3	62	9	9
Polyester	58.8	41	-	-
Bio-Resin	49.9	-	30	24
Flax Fiber/Linen	9.55	-	3	5
Total	-	103	42	38

3.3.5.2 Transportation

Raw materials for GFRC (polyester resin, glass fibers, remaining fillers and additives) were obtained from within the U.S. They were transported an average of 500 km to the manufacturing facility, and 1.2 kJ/cm^3 was calculated for transportation energy of GFRC.

Flax used in NFRCs was transported for extensive distances before being delivered to the plant. Although some amount of flax products are produced in North Dakota, a supplier for obtaining flax fibers could not be located by the manufacturer. Therefore, linen was obtained from India. However, flax fibers used in weaving were obtained from France.

The energy consumption for transporting products by trucks and sea vessels were calculated by using estimated transportation distances and energy intensities from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model version 1.8c. GREET is a widely accepted tool used for calculating transportation energy (Wang

2007; GREET 2009). Energy consumption associated with transporting flax products for both NFC composites are summarized in Table 5.

Table 5. Transportation energy consumption for linen used in NFRCs (Wang 2007; GREET 2009)

From - To	Mode of transportation	Distance (km)	Energy Intensity (kJ/ton-km)	NFRC I Energy Consumption (kJ/cm^3)	NFRC II Energy Consumption (kJ/cm^3)
France – Port	Land - trucks	500	1,200	0.2	0.3
Port – India	Sea	8,300	35	0.1	0.1
Port – Weaving Facility	Land - trucks	1,750	1,200	0.7	1.1
Weaving Facility – Port	Land - trucks	1,750	1,200	0.7	1.1
India – U.S.	Sea	15,000	35	0.2	0.3
Port – Pultrusion Plant	Land - trucks	500	1,200	0.2	0.3
Total	-	27,800	-	2.1	3.3

3.3.5.3 Manufacturing

The pultrusion technique was used to manufacture GFRCs and NFRCs. While 3.1 MJ/kg was reported for production energy (Suzuki 2005; Song, Youn et al. 2009), actual energy use from the manufacturing company was utilized during the study which included average electricity use of the company for composite production. Since the same machinery was used to pultrude, cut, and store both types of composites, energy intensity during manufacturing was assumed to be the same. Based on actual data from the company, electricity consumption was estimated to be 0.58 MJ per kg of composite. Consumed electricity was calculated from purchased electricity from the utility company, and includes supporting operations such as use of supporting tools and machinery, lighting, heating and cooling of the facility, and office electricity use.

There is a notable difference between pultrusion energy consumption in literature and calculated results using actual plant data; where the latter was 80% lower than published values. A possible explanation for this difference might be the size of the facility and thus throughput of composites. As the manufacturing capacity increases, electricity consumption per unit composite produced could decrease as a result of shared company overhead. Another possible reason for the variation in production energy might be due to the differences in plant machinery technologies such as air handling equipment, cutting tools, and packaging equipment. As for climatic factors, the location of the plant has 40% more heating degree days and 45% fewer cooling degree days than the U.S. average based on recent 12 months data (NOAA 2010). Therefore, a significant difference due to local climatic conditions was not expected to cause the large difference in production energy intensity.

Manufacturing energy consumption for each composite was based on actual data from the composite pultrusion company. However, reporting manufacturing energy consumption in MJ/kg units was not preferred since the functional unit used to compare composite alternatives was based on volume. To this end, the manufacturing energy intensity of the pultrusion plant was calculated to be 1.16 kJ/cm^3 of composite. By including upstream energy generation, transmission, and embodied energy of materials calculated by using the Franklin database based on U.S. average fuel mix (Norris 2004), manufacturing energy consumption results in 4.0 kJ/cm^3 of composite, which was used in this study.

3.3.5.4 Packaging

Regardless of the type of composite (GFRC or NFRC), similar amounts and techniques of packaging were used at the manufacturing plant. The finished products were placed on timber skids and then wrapped by using Low Density Polyethylene (LDPE). The amount of packaging required for a certain amount of composite varies since many parameters including geometry, purchased quantity and truck capacity play an important role during packaging. Therefore, yearly average consumption of these products was used to provide estimates of the expected consumption per unit volume of composite. Based on actual data received from the pultruded composites company, around 20 tons of LDPE was used each year together with approximately 240 tons of timber planks.

Energy consumption of LDPE varied within literature from 69.2 to 88.6 MJ per kg of LDPE (PlasticsEurope 2000; Patel 2003; Vink, Rabago et al. 2003; PlasticsEurope 2008). The mean of these data points, 78.9 MJ/kg was used in this study.

For timber planks, it was assumed that air dried softwood was used during packaging. Energy consumption of timber was taken as 0.3 MJ per kg of timber (FAO 1990). Equal amounts of packaging material were assumed for composite alternatives since they all had equal volume based on the selected functional unit. To this end, 0.42 kJ/cm^3 and 0.02 kJ/cm^3 were calculated for energy consumption related to LDPE and timber planks, respectively. Total energy consumption of the packaging phase then becomes 0.44 kJ/cm^3 for all composite alternatives.

3.4 DISCUSSION OF RESULTS

The life cycle energy consumption of GFRC and NFRCs are presented in Figure 4. The use of linen combined with bio-resin decreases the energy consumption of composites by almost 60% when compared to GFRC. The use of a thicker fabric, as in the case of NFRC II, has the potential to further decrease energy consumption by 5-10% with respect to a finer fabric as in NFRC I. Total energy consumption of GFRC was calculated to be 109 kJ/cm^3. This was lower for both flax composites where 49 kJ/cm^3 and 46 kJ/cm^3 were found for NFRC I and NFRC II, respectively.

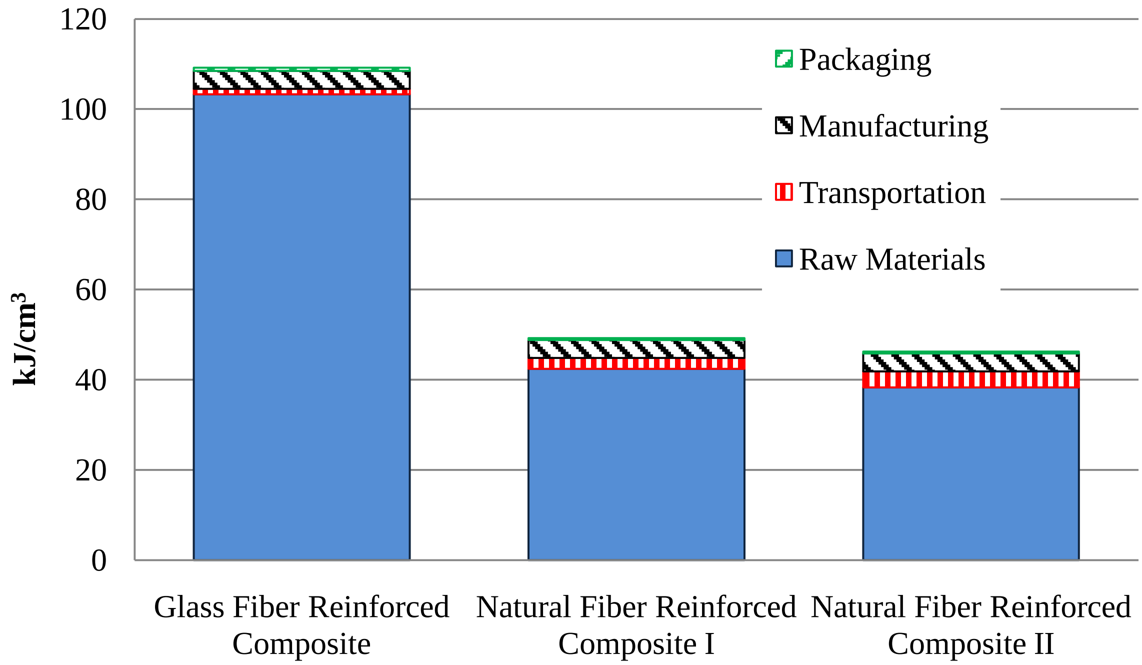


Figure 4. Life cycle energy consumption analysis results for composites

The majority of energy consumption in composites (90%) is from upstream raw materials as shown in Figure 4. Other processes such as transportation, manufacturing and packaging constitute small percentages in the product life cycle. Decreasing energy consumption of raw materials would be an effective strategy for future improvements having a focus on reducing energy consumption of composites. Using bio-resins instead of polyester, or natural fibers instead of glass fibers improves energy performance of the end product. The use of lighter flax fibers in large volumes replacing the amount of resin necessary contributes to lower consumption.

The GFRC density was calculated to be 2.0 g/cm^3 and was verified with the manufacturer to be within their expected range of results. The composites produced by using flax fibers in linen form resulted in lower densities of 1.13 g/cm^3 and 1.19 g/cm^3. Since the density of polyester is close to the density of bio-resin, the difference in these composites is due to flax fibers that are lighter than glass fibers.

Based on the assumed transportation distances, NFRCs consumed 2-3 times more energy than GFRCs. Flax fibers were transported an estimated total of 28,000 km starting from their cultivation to where they were used to manufacture composites in the U.S. A sensitivity analysis was performed to investigate the impact transportation distance has on the total energy consumption when flax fibers and linen are obtained from within U.S.

Flax cultivation in the U.S. takes place mostly in the Central Northern region where North Dakota is the major producer in the region (96% of U.S. flax cultivation). Given that a market is formed and a steady demand for flax fibers is available, the region is suitable to supply the internal flax fiber demand for the U.S. However, a company capable of weaving flax fibers into linen also needs to be conveniently located within the U.S.

For the purpose of the sensitivity analysis, these conditions were assumed to be satisfied. The total transportation distance was estimated to be 2,400 km, all to be transported on land by trucks. Transportation energy consumption for NFRCs decreased by more than 50% and became comparable to GFRCs when flax and linen were obtained from within the U.S. The results of the sensitivity analysis are presented in Table 6. The decrease in life cycle energy consumption of NFRCs was 5% for composites having high amounts of flax fibers.

Table 6. Results of sensitivity analysis for transportation

Composite	Original Assumptions (kJ/cm^3)	Original Assumptions (% of total energy consumption)	Obtaining Flax Products within U.S. (kJ/cm^3)	Obtaining Flax Products within U.S. (% of total energy consumption)
GFRC	1.2	1.1	1.2	1.1
NFRC I	2.4	5.2	1.0	2.3
NFRC II	3.5	8.7	1.5	3.7

3.4.1 Impact of Lifetime on Results

Due to lack of data on observed lifetime of NFRCs, the lifetime of alternate composites were assumed to be equal during calculations in the preceding portion of the study. However, the technical properties of GRFC and NFRCs are not the same. Although NFRCs were not intended for use in structural or mechanically demanding applications, differences in hygrothermal properties may result in variations in durability, and thus lifetime of composites with respect to each other.

The values presented in and conclusions derived from Figure 4 were based on assuming equal lifetime for composite alternatives. The energy consumption ratio of composite alternatives has been recalculated based on the ratio of product lifetime. Results for both NFRC I and NFRC II are presented in Figure 5.

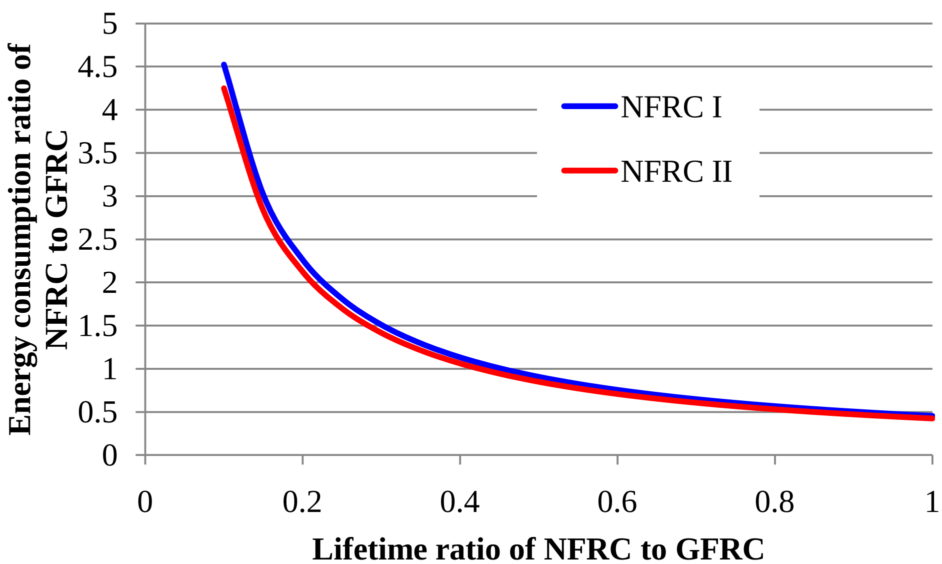


Figure 5. Impact of composite lifetime on energy consumption results

Distributions in Figure 5 indicate that GFRC becomes the preferred alternative in terms of life cycle energy consumption once the lifetime ratio of NFRCs to GFRC becomes lower than 0.45 (i.e. 9 years of expected lifetime for NFRC compared to 20 years for GFRC).

Results demonstrate the impact of lifetime on comparative life cycle studies. Conclusions that can be drawn from such studies are dependent on the assumed ratio of product lifetime. The selection of product lifetime in comparative studies may alter results from one product to another. Therefore, life cycle studies that do not adequately address lifetime of products are not definitive and may lead to misleading conclusions when product characteristics and intended applications are not taken into account. This outcome was a motivation for the research that followed.

3.5 SUMMARY

The novel aspect of this research was the study of a pultruded natural fiber composite by using a bio-resin. Natural fibers have been incorporated in composites for some time, although by other means of production. Pultrusion is one of the least energy consuming production methods and so pultruding flax fibers together with a bio-resin has the potential to create an environmentally friendly composite.

Life cycle energy consumption was quantified for two different composites, NFRC and GFRC. Glass fiber reinforced composites were compared to two new alternatives produced by using linen having different thicknesses, pultruded together with bio-resins. Considering the life cycle of a pultruded composite product starting from raw material extraction through the use phase, flax fiber reinforced composites were found to consume 55-60% less energy compared to

GFRC when both composite alternatives were assumed to have equal lifetime. The use of less energy intensive bio-resin instead of polyester as well as the incorporation of flax fibers in linen form as a replacement to energy intensive glass fibers contributed to the NFRC energy savings.

Transportation contributes 5-10% to the total energy consumption of NFRCs, and 1% to GFRCs. A sensitivity analysis of flax fibers transportation was performed, where flax fibers produced in Western Europe, transported to India, and the U.S. was compared to cultivating and processing flax within the U.S. Results indicate that transportation energy of NFRCs could be halved by producing flax within the U.S. Therefore, with increasing internal demand, all parties would benefit by developing flax fiber production and weaving facilities that can produce a variety of products for use in various industrial sectors.

In accordance with other published studies, flax fiber composites resulted in lighter composites that provide a great advantage over glass fiber reinforced composites especially in the automotive industry due to reduced vehicle weight and thus increased fuel efficiency. The majority of energy consumption in composites results from raw materials extraction and composite production phases. These two stages account for 97% of the total energy use during the life cycle of GFRC and close to 90% for NFRC. There is potential to further reduce the energy consumption of composites by exploring less energy intensive raw materials.

Although pultrusion is one of the most energy efficient methods for composite production, further research is needed to verify the energy intensity of this method for composite production. Energy intensity calculated from actual plant data yielded 80% less energy usage compared to published data. Although industry wide conclusions should not be derived from this result, the degree of variation is significant.

The composites manufacturer expected equal design life for both composites. Since adequate lifetime information from past observations was not readily available for flax fiber reinforced composites, the life cycle energy consumption was analyzed based on equal lifetime for composite alternatives. However, a sensitivity analysis on the impact of lifetime on results indicates that results are highly dependent on the ratio of lifetime of NFRC to GFRC. Results presented for composite alternatives in Figure 4 by assuming equal lifetime may favor NFRCs over GFRC for life cycle energy consumption. However, this conclusion is reversed when the ratio of expected lifetime of composites falls below 0.45.

One of the important outcomes of this research was the identification of product lifetime as an area that requires further research. Reviewing life cycle studies of building products in general revealed that product lifetime was a topic that was commonly understated. Therefore, the impact of lifetime data on LCA results became the focus in the research that followed.

4.0 IMPACT OF LIFETIME ON U.S. RESIDENTIAL BUILDING LCA RESULTS

4.1 INTRODUCTION

The built environment is a major contributor to both social and economic development and represents a large portion of real capital in many countries; but it is also a primary source of environmental impacts. Furthermore, existing building stock requires continuous investments for repair and renovations (Hovde 2004). Of the 2.5 billion metric tons of non-fuel materials that moved through the economy in 1990, over 70% were used for construction (Fernandez 2006). In 2010, buildings were estimated to account for close to 40% of U.S. primary energy consumption and greenhouse gas emissions (DOE 2009).

The notion that building structures that would last for centuries is the best environmental solution to current problems does not match with our existing building use trends and knowledge of the built environment. Buildings will be replaced with newer designs that are more suited toward the needs of future occupants. This concept should be considered during initial design, construction, and environmental and economic analysis.

In many cases, building lifetime is governed by factors not directly related to the building design. For residential buildings in the U.S., lifetime is more directly related to social acceptability factors rather than durability or structural problems (Winistorfer 2005).

Life cycle assessment (LCA) is a tool that can quantify the environmental impacts of buildings (Optis 2010). However, many building LCA studies do not adequately address the actual lifetime of residential buildings and building products, but rather assume a typical value, say 50 years (Adalberth 1997a; Winther 1999; Keoleian 2001; Thormark 2002). This study addresses this gap by determining the impact of lifetime on residential building LCA results. Including accurate lifetime information in LCA allows a better understanding of the life cycle impacts, ultimately enhancing the accuracy of LCA studies.

This research focused on refining the U.S. residential building lifetime, as well as the lifetime of commonly used interior finishes such as paint and carpet, to improve LCA results. Detailed descriptions of residential building lifetime distributions and trends were presented. Existing data on product emissions were synthesized to form statistical distributions that were used instead of deterministic values. Product emissions data are used to calculate life cycle impacts of a residential model that is based on median U.S. residential home size. Results were compared to existing residential building LCA literature to determine the impact of using updated, statistical lifetime data. A Monte Carlo analysis was performed for uncertainty analysis. Sensitivity analysis results were used to identify critical parameters within the LCA results.

4.1.1 Building use and lifetime

Although a quantitative analysis for residential building lifetimes has not been conducted, the general consensus is that residential buildings have lifetimes ranging from 50 to 100 years (Adalberth 1997a; Adalberth 1997b; Anderson 1999; Winther 1999; Borjesson 2000; Fay 2000; Keoleian 2001; Anderson 2002; Scharai-Rad 2002; Thormark 2002; Lippke 2004; Mithraratne 2004; Winistorfer 2005; Nebel 2006; Itard 2007; Nassen 2007; Kellenberger 2009). However, building lifetimes used in LCA studies are often arbitrarily selected as explicitly stated in many studies (Adalberth 1997a; Adalberth 1997b; Anderson 1999; Winther 1999; Borjesson 2000; Fay 2000; Keoleian 2001; Anderson 2002; Thormark 2002; Lippke 2004; Winistorfer 2005; Itard 2007; Kellenberger 2009).

4.1.2 Factors that influence lifetime of building products

Reasons behind replacing interior finishes can be grouped into three categories: failure, dissatisfaction, or change in occupant needs (Cooper 2004). Failure is related to durability of materials and is the only category that can be designed or influenced by the manufacturer. All materials degrade over time as they are used. In addition to normal wear and tear, UV light, humidity, temperature, biological factors, installation and maintenance procedures are key degradation factors that affect durability of interior building products.

Dissatisfaction is mostly associated with styling changes, fashion trends, or new products being introduced to the market. In this case, consumers are not necessarily motivated by rational cost-benefit considerations, but rather by their desires and perceptions. Occupant needs may change over time even at the same residence, when occupants have children or become elderly for instance.

In practice, the actual lifetimes of various building products are shorter than what they had been designed for (Ashworth 1996; Plat 1999). Occupant behavior influenced by societal trends is an important factor that influences the lifetime of products (Hermans 1999; van Nunen 2002; Guiltinan 2009). However, models that capture the effects of consumer behavior on product lifetimes are not widely used. Lifetime estimation methods that can capture the effects of consumer behavior are a necessary step towards modeling lifetime (Cooper 2003).

4.2 METHODS

Methods used to gather and process data, together with assumptions made and equations used to calculate results are described in this section. Data sources for residential building lifetime and interior finishes are presented. Multiple data points enabled the use of distributions for variables. Procedures used to fit distributions, and uncertainty analyses of results using the Monte Carlo method are described. Results were applied to a residential model for interpretation. A description of the residential model is presented together with related assumptions. Data on different life cycle phases of a residential building were also analyzed in order to compare interior renovation impacts to life cycle impacts.

4.2.1 Data sources

Multiple data sources were used to determine the lifetimes for this study. Data published by the U.S. Census Bureau were used extensively for building related statistics (EIA 2005; Census 1997; Census 1999; Census 2001; Census 2003; Census 2005; Census 2007; Friedman 2008; Census 2009; Census 2009; Census 2009). BEES v4.0 (Lippiatt 2008), and the Ecoinvent v2 and ETH-ESU LCI databases incorporated in Simapro v7.1 software (SimaPro) provided the majority of environmental emissions data for building products. Traci 2 v3.01 (Bare 2003) was used for impact assessment of inventory data. See Table 7 for environmental emissions data of interior finishes.

4.2.1.1 Residential Building lifetime

Accurate data on residential building lifetime was vital since building lifetime determines the number of interior renovations. Data on U.S. residential building stock was published by the U.S. Census Bureau under the 2009 American Housing Survey microdata, which had a sample size of over 70,000 residences (Census 2009). No other governmental or public source provided such a large number of reliable data points on the U.S. housing stock. Survey microdata included data for when a building was built and whether it was demolished since the last survey. The difference between these two values provided the lifetime for that building. A large dataset including over 3,700 data points for building lifetime (i.e. buildings that were demolished since previous survey) was gathered from microdata by this approach.

A caveat of using this data source was that the type of building was not recorded for buildings that were coded as demolished. Therefore, average lifetime of different building types could not be calculated directly from this primary source. However, it was possible to reach a conclusion regarding average lifetime of single-family residential buildings based on three supporting analyses.

On a national scale, single-family detached houses and apartments form 63% and 25% of the U.S. building stock, respectively (Census 2009). The remaining portion being equally divided between single-family attached homes and mobile units. The difference in average building lifetime of single-family detached houses and apartments was investigated. Average age of existing single-family detached houses and apartments including two or more units were calculated to be 42.4 years and 44.1 years respectively from the 2009 American Housing Survey microdata (Census 2009). Average age of existing buildings is different from building lifetime, since the building needs to be demolished in order to calculate its lifetime. Nevertheless, the difference in mean age of existing buildings between these two categories was found to be insignificant compared to the inherent uncertainty of building age.

Existing buildings were separated according to type and year built. The ratio of single-family detached houses to the combined total of single-family detached houses and apartments varies within a range of 60-80% over the decades but has an almost constant value of 70%. Based on analyzed data from the 2009 American Housing Survey, evidence to support that single-family detached houses and apartments have different lifetimes was not found, and so they were assumed to be the same throughout the current study. A study by O'Connor (2004) surveying 227 demolished buildings found that only 8 were demolished due to structural reasons, and that buildings were usually demolished due to changing land values and occupant needs. Results of this study support our assumptions since the effects of social factors independent of building type were found to determine building lifetime in most cases.

Buildings built prior to 1920, which constitute 7% of the existing U.S. building stock, were presented in a single category in the 2009 American Housing Survey results (Census 2009). The 2008 New York Housing Survey divides this category into two sections: structures built between 1900-1919, and those built pre-1900, with ratios of 75% and 25% respectively (Friedman 2008). The same ratios of 75% and 25% were used to further classify pre-1920 buildings on a national basis into two separate categories of 1900-1919, and pre-1900.

The methods described here were used on past surveys as well to observe the trend in residential building lifetime. Survey results dating back to 1997 were published by the U.S. Census Bureau and were used in this study to plot trends in residential building lifetime (Census 1997; Census 1999; Census 2001; Census 2003; Census 2005; Census 2007; Census 2009).

4.2.1.2 Products investigated

Interior finish products that are commonly replaced within U.S. residential buildings were investigated in this study. Interior paint is usually applied in all residential buildings to some degree, and therefore was included. Multiple flooring alternatives including carpet, hardwood, linoleum, vinyl, and ceramic were also considered.

Data points for lifetime and environmental emissions of interior finishes that were used in the study are given in Table 7. In some instances, a range of values was provided for lifetime of products rather than a single value (Gunther 1997; Seiders 2007). In these cases, a uniform distribution was assumed for the given range of values. For long lasting products such as hardwood and ceramic, some sources indicated that the product was expected to last as long as the residential building, therefore not necessitating any interior renovation (Gunther 1997; Seiders 2007). Due to large uncertainty associated with predicting product lifetime several decades into the future, the lower lifetime limit was selected during analysis, i.e. 75 years when lifetime was given as 75 or more years.

Table 7. Data points for lifetime and environmental emissions of interior finishes

	Paint	Carpet	Hardwood	Linoleum	Vinyl	Ceramic
Lifetime (Years)	3 (NYC), 4 (Lippiatt 2008), 5 (Scheuer 2003; Kelly 2007), 7 (Pullen 2000), 8 (Mithraratne 2004), 10 (Adalberth 1997a; Hed 1999; Fay 2000; Keoleian 2001), 15 (Seiders 2007)	5 (Gunther 1997; Anderson 2002), 8 (Potting 1995; Keoleian 2001), 8-10 (Seiders 2007), 9 (Petersen 2004), 10 (Pullen 2000), 11, 15 (Lippiatt 2008), 12 (Scheuer 2003; Mithraratne 2004), 17 (Adalberth 1997a)	10 (Nebel 2006), 20 (Anderson 2002; Nebel 2006), 25 (Nebel 2006), 40 (Jonsson 1997; Jonsson 1999), 45 (Scharai-Rad 2002; Petersen 2004), 50 (Adalberth 1997a; Mithraratne 2004; Nebel 2006), 50+ (Gunther 1997), 100+ (Seiders 2007)	5-40 (Paulsen 2003), 7-40 (Gunther 1997), 15 (Potting 1995), 15-22.5 (Petersen 2004), 20 (Costmodelling ; Gorree 2002), 25 (Jonsson 1997; Jonsson 1999; Seiders 2007), 30 (Lippiatt 2008)	7-40 (Gunther 1997), 8 (Potting 1995), 9, 23 (Petersen 2004), 17 (Mithraratne 2004), 18 (Scheuer 2003), 20 (Jonsson 1997; Suzuki 1998; Jonsson 1999; Pullen 2000; Keoleian 2001; Paulsen 2003), 40 (Lippiatt 2008), 50 (Seiders 2007)	20 (Anderson 2002; Nicoletti 2002), 30 (Mithraratne 2004), 50 (Lippiatt 2008), 75 (Scheuer 2003), 75-100 (Seiders 2007)
Energy (MJ/m^2)	3.0, 3.7, 7.2 (Lippiatt 2008), 3.6 (Adalberth 1997a), 6.6, 6.7, 6.8 (SimaPro), 11 (Keoleian 2001),	89, 102, 111, 122, 131, 209, 214, 239, 242, 242, 253, 274, 276, 282, 285, 296, 320 (Lippiatt 2008), 171 (Interface), 183 (BPS)	250 (Gunther 1997), 314, 402, 582 (Scharai-Rad 2002), 530, 530, 550, 920 (Nebel 2006)	57.7 (Jonsson 1997), 130 (Gunther 1997), 161 (Paulsen 2003), 276, 305 (Lippiatt 2008)	56 (Jonsson 1997), 130[a] (Scheuer 2003), 165 (Gunther 1997), 170 (Paulsen 2003), 245 (Lippiatt 2008)	347 (Lippiatt 2008)
Global Warming Potential (kg CO_2E/m^2)	0.05, 0.09, 0.18 (Lippiatt 2008), 0.26, 0.27, 0.37, 0.38 (SimaPro)	5, 5, 10, 11, 12, 12, 12, 12, 13, 13, 15, 17 (Lippiatt 2008), 10.6 (Interface), 11.3 (BPS)	4.4, 5.9, 7.1, 12.7 (Nebel 2006), 29 (Gunther 1997), 44, 56, 56 (Scharai-Rad 2002)	1.6 (Jonsson 1997), 2.6 (Potting 1995), 6, 10 (Lippiatt 2008), 17 (Gunther 1997)	4.1 (Jonsson 1997), 9.4 (Potting 1995), 12 (Gunther 1997), 10 (Lippiatt 2008)	23 (SimaPro), 26 (Lippiatt 2008)

Table 7 (continued)

Acidification (g H+/m^2)	0.03, 0.04, 0.08 (Lippiatt 2008), 0.06, 0.09, 0.12, 0.15 (SimaPro)	2, 2, 2, 2, 3, 4, 5, 5, 5, 5, 5, 5, 6, 8, 8 (Lippiatt 2008), 2.1 (BPS), 2.5 (Interface)	5200, 5400, 5700, 11300 (Nebel 2006)[b], 5100, 6100, 6600 (Scharai-Rad 2002)[b]	1.2 (Gunther 1997), 5.6, 6 (Lippiatt 2008)	2 (Gunther 1997), 6 (Lippiatt 2008),	4.3 (SimaPro), 9.6 (Lippiatt 2008)
Eutrophication (g N/m^2)	0.00 (Lippiatt 2008), 0.03, 0.53, 0.96, 1.29 (SimaPro)	2, 2, 2, 2, 3, 3, 4, 5, 10, 11, 12, 13, 13, 14, 15 (Lippiatt 2008), 10 (Interface), 12 (BPS)	2, 31, 38 (Scharai-Rad 2002), 35, 35, 38, 81 (Nebel 2006)	18.9, 23.3 (Lippiatt 2008)	0.02 (Jonsson 1997), 1.7 (Lippiatt 2008)	4 (Lippiatt 2008), 8.3 (SimaPro)
Smog (g NO_x/m^2)	0.5, 0.6, 1.0, 1.1 (SimaPro), 16.2, 16.5, 16.9 (Lippiatt 2008)	24, 24, 24, 25, 28, 33, 47, 50, 58, 58, 61, 63, 64, 64, 64, 64 (Lippiatt 2008)	-	119, 125 (Lippiatt 2008)	40 (Lippiatt 2008)	38 (SimaPro), 122 (Lippiatt 2008)

Notes: The sign '+' after a number indicates that expected lifetime was more than the given value.

Multiple references after a data point indicate multiple occurrences in different studies.

[a] Average values were used to convert mass to volume

[b] TRACI characterization factors were used to convert SO_2 into g H+

4.2.2 Uncertainty in variables

Addressing uncertainty plays a key role in interpreting results of life cycle studies. The use of distributions for lifetime and environmental emissions data was preferred over using deterministic values since a realistic uncertainty analysis was not possible otherwise. Statistical analysis tool @Risk v5.5 was used for uncertainty analysis (Palisade 2009).

The chi-squared test was used to fit distributions. A goodness-of-fit test is an inferential procedure used to determine how well a given set of data fits a chosen distribution (Sullivan 2007). Originally developed by Pearson in 1900, the chi-squared test is the oldest inference procedure that is still used today in its original form (Johnson 2003). A Weibull distribution provided the best fit for residential building lifetime and lifetime of most interior finishes. The use of this distribution to model lifetime is common, supported by standards and guidelines (Kececioglu 1991; ASTM 2003; ASTM 2005).

Developments in the field of building LCAs have not been matched by accurate emissions data for building products (Bowles 1995). Existing databases do not sufficiently cover the vast array of products that exist today. Few data points were located for some building products' environmental impact categories due to lack of reliable publications and confidentiality concerns from the manufacturer's perspective. Therefore, triangular or uniform distributions were defined for variables where an adequate number of data points could not be found.

Since variables were defined as distributions, interior renovation impact results were also calculated as distributions having a mean and a 90% confidence interval. Monte Carlo simulation was used to calculate uncertainty in results. Monte Carlo is a statistical method that uses random values from input parameters and presents a distribution for the output parameter (Woller 1996;

Soratana 2010). The likelihood of potential outcomes can thus be observed from resulting distributions; 20,000 iterations were used for this analysis.

4.2.3 Interpretation of results through a developed residential model

The goal of this study was to determine the impact of lifetime on residential building LCA. Interior renovation impacts over the life cycle of a residential building model were calculated by using the determined distributions for building lifetime, building product lifetime, and environmental impact of products. A residential model based on median U.S. residential building size was used to calculate life cycle environmental impacts of interior renovation. Existing single-family detached homes have a median size of 167 m^2 based on the 2009 American Housing Survey microdata, which was used to determine the size of the residential model in this research (Census 2009). The mean single family detached home size of 206 m^2 for existing residential buildings calculated from the same microdata places more emphasis on larger homes as compared to the distribution of home size and therefore was not preferred.

A 4-bedroom, 2-bathroom home was assumed for the residential model with the following specifications: Ceiling and interior walls were painted, bathroom walls were painted up to half height and the remaining portion covered with ceramic, wall to wall carpeting for the home except for kitchen where vinyl covering was assumed. In total, 550 m^2 of painted surface area, 45 m^2 of ceramic, 122 m^2 of carpeting, and 21 m^2 of vinyl were calculated for the residential model. The interior painted surface area was highly dependent on design, or architectural model of the home, and so a uniform distribution of 500-600 m^2 was used during calculations to account for the high level of uncertainty associated with painted surface area.

Equation 2 was used to calculate energy use and environmental emissions of interior finishes over the life cycle of a building. The given equation was used to calculate interior renovation impacts and does not include initial construction stage material use. A 5% waste factor was assumed for all floor-covering materials as construction loss from cutting and fitting of products. This value was based on manufacturer recommendations and examples of its use exist in literature (Keoleian 2001). The same type of product as the previous layer was assumed to be used during interior renovation (e.g. carpet replaced with carpet) throughout the lifetime of the building.

Equation 2.

$$\left\lfloor \frac{\text{building lifetime (years)}}{\text{product lifetime (years)}} - 1 \right\rfloor \times \frac{\text{product emissions (kg } CO_2E/m^2)}{\text{efficiency } (m^2/m^2)} \times \text{application area } (m^2)$$

4.2.4 Residential building energy consumption over different life cycle phases

Calculating interior renovation impacts of the residential model enables comparisons to be made between different life cycle phases of a residential building. A distinction can also be made between residential buildings built by using regular materials and techniques, and those that are designed to consume less energy during their use phase, or low-energy homes. Consuming less energy during the use phase, which is the dominating phase for regular homes, increases the relative importance of other life cycle phases including interior renovation.

Pre-use phase, which includes initial materials use, construction, and associated transportation for both activities, has a mean energy consumption of 4.0 GJ/m^2 with a range of 1.7-7.3 GJ/m^2 based on results of multiple case studies on residential buildings (Keoleian 2001; Thormark 2002; Lippke 2004; Mithraratne 2004; Winistorfer 2005; Nassen 2007; Sharrard

2008). Pre-use energy consumption of low-energy homes was found to have a higher mean of 6.2 GJ/m^2 with a range of 4.3-7.7 GJ/m^2 (Winther 1999; Keoleian 2001; Thormark 2002). A contributing factor for increased energy intensity in low-energy homes is the thicker shell and the high embodied energy associated with insulation products that are applied for weatherization.

Mean energy consumption during the use phase of existing single-family detached homes in the U.S. is given by the Energy Information Administration to be 0.45 GJ/m^2/yr (EIA 2005). A separate category for low-energy buildings was not present in this primary source. Use phase energy consumption of low-energy homes was estimated to be 0.18 GJ/m^2/yr with a range of 0.07-0.41 GJ/m^2/yr from published case studies (Winther 1999; Keoleian 2001; Thormark 2002).

Demolition energy and transportation of waste was found to be 0.1-1% of life cycle energy regardless of building type and so was neglected during calculations (Keoleian 2001; Scheuer 2003; Winistorfer 2005; Ortiz 2009).

Total energy consumption over the life cycle of the residential model can then be modeled by using Equation 3.

Equation 3.

$$[\text{pre-use (GJ/m}^2) \times \text{area (m}^2)] + [\text{use (GJ/m}^2\text{/yr)} \times \text{area (m}^2) \times \text{building lifetime (years)}]$$

4.2.5 Sensitivity analysis and validation

Energy consumption and environmental emissions of products over the residential buildings life cycle are a function of multiple variables including multiple products. After a Monte Carlo simulation was performed for an environmental impact category, a sensitivity analysis was conducted to identify variables that contributed most to interior renovation impacts of the residential model.

Paint and flooring alternatives were assumed not to influence residential building lifetime and were also assumed not to affect renovation cycles of other products included in the analysis. This enabled the use of independent variables in the sensitivity analysis.

The findings were applied to published case studies to compare results. The study by Keoleian et al. (2001) on residential building LCA that is frequently cited by other researchers, was chosen to validate results. The applicability of research findings and the level of detail that was presented in the article were also considered during selection.

4.3 RESULTS AND DISCUSSION

4.3.1 Residential building lifetime

Average residential building lifetime was calculated to be 61 years with a standard deviation of 25 years based on the 2009 American Housing Survey. Lifetime is expected to fall within a large range of 21 years to 105 years with 90% confidence. Weibull distribution with a shape parameter of 2.8 and a scale parameter of 73.5 provided the best fit to model lifetime of residential buildings (i.e. a chi-square statistic of 0.26 for Weibull, compared to 23 and 69 for lognormal and normal distributions, respectively). By using the same method, residential building lifetime was also calculated from previous surveys. Figure 6 presents lifetime distribution results for housing surveys conducted from 1997 to 2009.

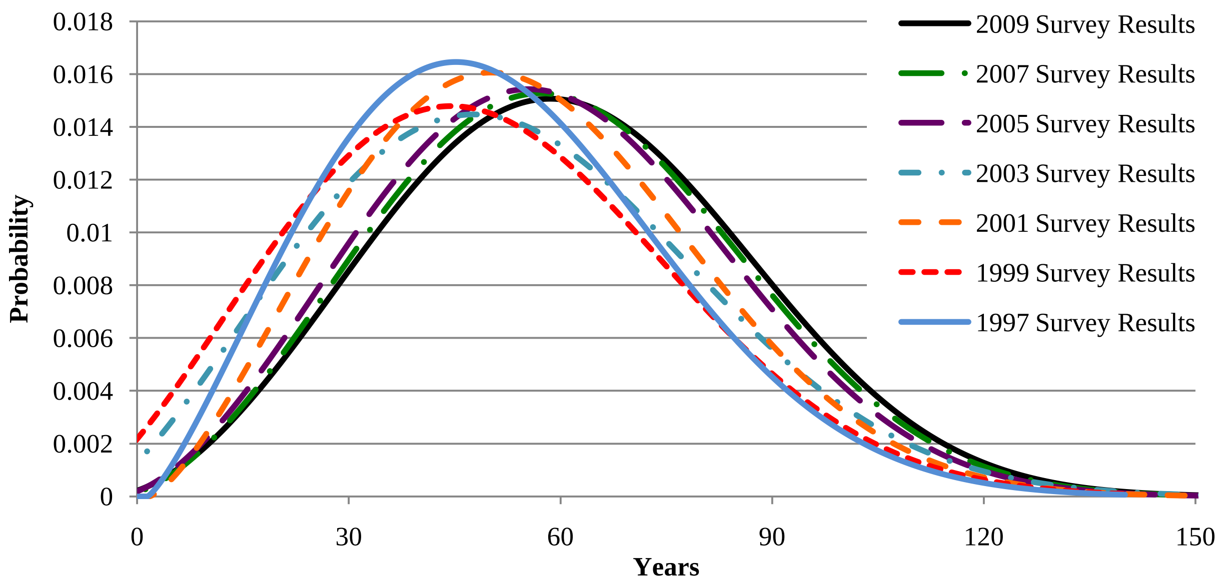


Figure 6. Lifetime distribution of residential buildings calculated from multiple American Housing Survey microdata

4.3.2 Product lifetimes and environmental emissions

Table 8 presents the mean and coefficient of variation values for lifetime, energy consumption, and environmental emissions data for each product. The coefficient of variation is defined as the ratio of the standard deviation of a distribution to its mean, and is a measure of dispersion in data. Table 8 also presents the type of distribution used for each variable, which were developed as described in Chapter 4.2.2.

The chi-square statistics for commonly applied distributions presented in Table 9 were used to fit distributions to product lifetime variables. Distribution alternatives that not only provided a good fit to existing data, but also resulted in logical extrapolations beyond the given dataset were considered. Based on these requirements, the Weibull distribution presented the best fit for paint, carpet, hardwood, and linoleum. The use of a Weibull distribution was preferred over a normal distribution for lifetime of vinyl. However, a sensitivity analysis was conducted to determine the impact of selecting a different distribution from the ones given in Table 9.

Table 8. Mean values, coefficient of variation, and the type of distribution for each variable

	Paint	Carpet	Hardwood	Linoleum	Vinyl	Ceramic
Lifetime (Years)	6.9 (0.39, w)	10 (0.32, w)	42 (0.52, w)	22 (0.19, w)	22 (0.45, w)	48 (0.45, u)
Energy (MJ/m^2)	6.8 (0.41, t)	220 (0.31, t)	570 (0.44, u)	200 (0.40, t)	160 (0.41, t)	350 (0.08, u)
Global Warming Potential (kg CO_2E/m^2)	0.2 (0.32, t)	11 (0.28, t)	38 (0.33, t)	10 (0.58, u)	9.3 (0.31, t)	25 (0.12, u)
Acidification (g $H+/m^2$)	0.1 (0.41, t)	5.0 (0.33, t)	6,300 (0.23, t)	4.5 (0.41, t)	4.0 (0.41, t)	7.0 (0.25, u)
Eutrophication (g N/m^2)	0.8 (0.58, u)	8.5 (0.50, u)	62 (0.52, t)	21.0 (0.14, u)	1.0 (0.58, u)	6.0 (0.58, u)
Smog (g NO_x/m^2)	17 (0.02, u)	50 (0.23, t)	-	120 (0.05, u)	40 (0.14, u)	80 (0.58, u)

Note: Numbers in parentheses represent the coefficient of variation for that distribution. Letters that follow denote the type of distribution used, where, w=Weibull, u=Uniform, t=Triangular.

Table 9. Chi-square statistic for different distributions

χ^2	Paint	Carpet	Hardwood	Linoleum	Vinyl	Ceramic
Lognormal	0.09	0.00	0.15	NA	7.54	0.00
Normal	0.09	0.33	5.69	0.40	4.77	0.00
Triangular	0.45	0.67	6.08	0.00	8.85	1.33
Uniform	0.09	1.33	5.69	0.00	7.54	0.00
Weibull	**0.09**	**0.00**	**0.15**	**0.40**	**7.54**	**NA**

4.3.3 Environmental emissions of the residential model

Impacts of interior renovation over the life cycle of a residential building were quantified. Table 10 presents the energy consumption and environmental emissions of products that were applied to the residential model. Results from all products used in the residential model are combined for each impact category and presented together with a range of results with a 90% confidence interval and the associated standard deviation for the resulting distribution. The combined results represent interior renovation impacts throughout the lifetime of the residential model.

Table 10. Environmental impacts of interior renovation for the residential model

	Lower Bound	Mean	Upper Bound	Coefficient of variation
Energy (GJ)	38	220	500	0.64
Global Warming Potential (t CO_2E)	1.9	11	24	0.63
Acidification (kg H+)	0.8	4.6	11	0.67
Eutrophication (kg N)	1.7	10	24	0.71
Smog (kg NO_x)	28	130	270	0.57

Note: Lower and upper boundaries are for a 90% confidence interval

4.3.4 Comparing interior renovation to different life cycle phases of the residential model

Environmental impacts of interior renovation over the life cycle of the residential model were compared to different life cycle phases of a residential building. For the model home considered, Figure 7 shows the significant difference in average energy consumption of a regular home and a low-energy home, mainly due to reduced use phase energy consumption.

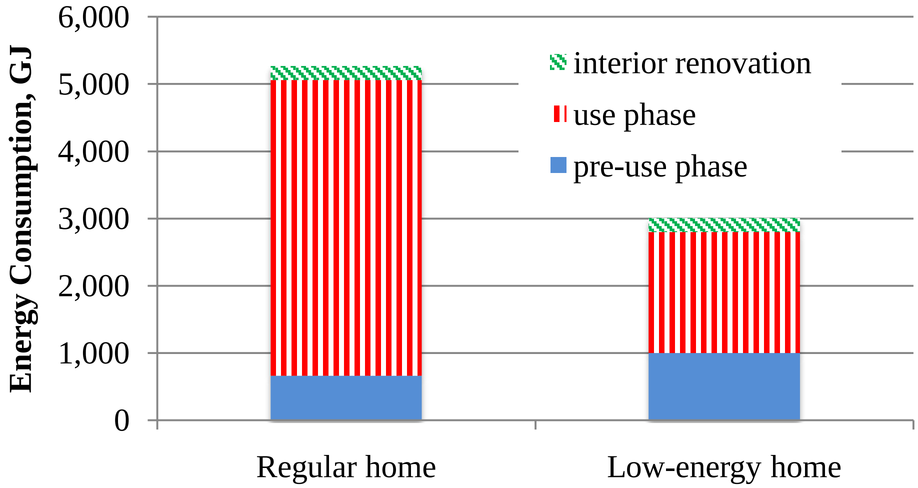


Figure 7. Energy consumption of a regular home and a low-energy home. Mean values are presented for different life cycle phases.

Comparing the distribution of results for different life cycle phases presents their relative importance. Energy consumption of interior renovation compared to pre-use phase energy consumption was calculated to have a mean of 34% for regular homes, and 22% for low-energy homes. Figure 8 shows distribution of results together with ranges for the 90% confidence interval. The ratio of interior renovation energy to life cycle energy of residential buildings was found to have a mean of 3.9% for regular homes and 7.6% for low-energy homes. Figure 9 shows distribution of results together with a 90% confidence interval.

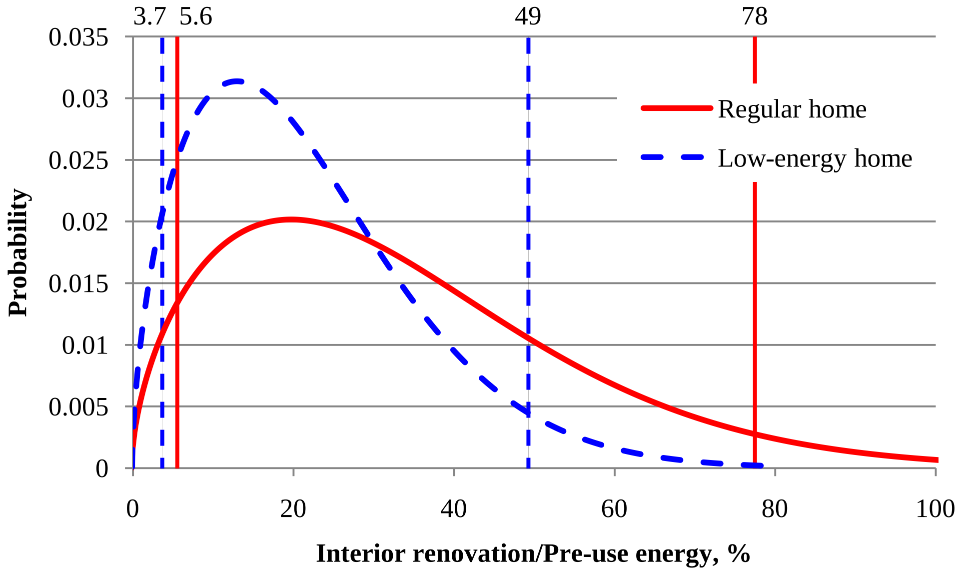


Figure 8. Distribution for the ratio of interior renovation energy to pre-use phase energy. Given error bars are for a 90% confidence interval

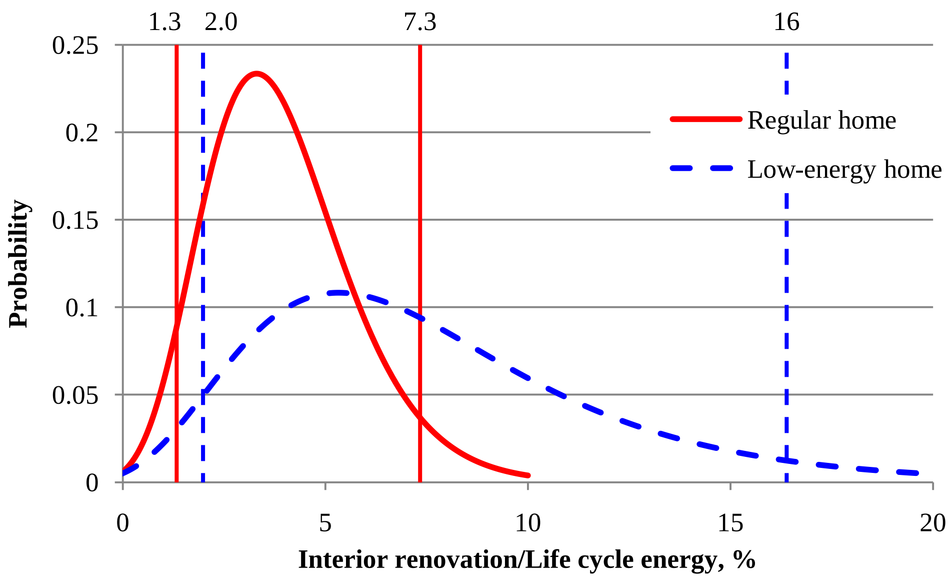


Figure 9. Distribution for the ratio of interior renovation energy to life cycle energy. Given error bars are for a 90% confidence interval

Techniques and materials that improve energy efficiency during the use phase of a building exist today, and are being increasingly applied to new residential constructions. The increase in the number of low-energy buildings signifies public interest towards efficiency and preservation, which will further drive building efficiencies higher. As buildings become more efficient, their use phase emissions will decrease, which will increase the relative importance of interior renovation over the life cycle of a building.

4.3.5 Sensitivity analysis

Monte Carlo analysis uses random inputs from a given dataset and outputs possible results in the form of a probability distribution. The sensitivity of results to changes in variables can also be quantified with a Monte Carlo analysis. Statistical analysis tool @Risk v5.5 was used for uncertainty analysis in this study with distributions given in Table 8 used as input.

Sensitivity analysis was performed to determine which variables had the greatest impact on interior renovation results from the residential model. Figure 10 presents results for energy consumption analysis. A positive regression coefficient indicates that results are proportional with changes in that category, whereas negative values indicate an inverse proportionality. A greater magnitude for the coefficient implies greater impact of that variable on results.

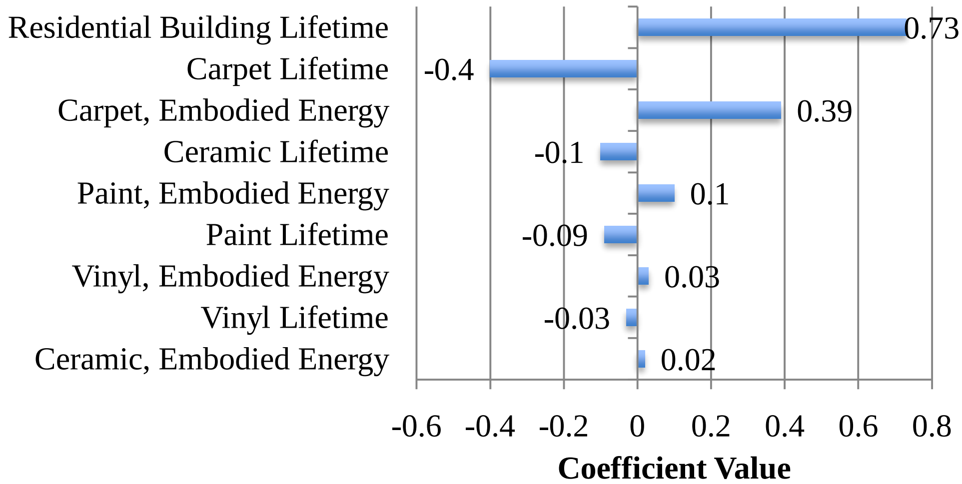


Figure 10. Sensitivity analysis results for energy consumption of the residential model, ranked based on decreasing influence to results

Results of sensitivity analyses should be used to identify hotspots and ultimately improve accuracy of LCA results. More accurate data should be sought for parameters having the greatest impact to improve accuracy of the study. Lifetime data and energy consumption of several interior renovation products were found to equally affect results for the residential model. Therefore, assuming an arbitrary lifetime for products would decrease accuracy as much as choosing a generic emissions factor for building products.

Residential building lifetime was found to have the greatest impact on interior renovation impacts. Following building lifetime, carpeting was found to have the most impact on results. Therefore, a recommendation for future LCAs involving similar materials and conditions would be to focus more on finding accurate data for carpeting compared to other interior finish products.

An additional sensitivity analysis was carried out on distribution selections since different distributions can be selected for a variable. As described in Chapter 4.2.2, selections were based on chi-square test results for the fit between data and proposed distributions. In order to test the impact of distribution selection on end results, distributions different from the ones shown in Table 8 have been chosen for interior finishes (i.e. the second best distribution from Table 9), and results recalculated. A lognormal distribution was assigned to represent lifetime of paint, carpet, and ceramic, and a normal distribution was assigned to lifetime of vinyl. Life cycle impacts of interior renovation presented in Table 11 show minimal variation in the statistical properties of variables when compared to results in Table 10, and therefore the impact of choosing the next best-fit distribution on end results were found to be negligible.

Table 11. Environmental impacts of interior renovation for the residential model using 2. best distributions to define lifetime

	Lower Bound	Mean	Upper Bound	Coefficient of variation
Energy (GJ)	38	230	530	0.70
Global Warming Potential (t CO_2E)	1.7	11	26	0.67
Acidification (kg H+)	0.7	4.8	12	0.71
Eutrophication (kg N)	1.5	10	25	0.73
Smog (kg NO_x)	25	120	260	0.58

Note: Lower and upper boundaries are for a 90% confidence interval

4.3.6 Validation of results

A study by Keoleian et al. focused on life-cycle energy consumption of a 228 m^2 single-family house in the U.S. (Keoleian 2001). A 50-year residential building lifetime was assumed in the analysis. Renovation impacts have been presented in detail, which allowed results to be directly compared. A description of materials included in the study, together with assumed lifetime and embodied energy data were provided. Renovation cycles were set at 10, 8, and 20 years for paint, carpet, and vinyl, respectively.

Interior renovation impacts have been revised by updating both residential building and building products lifetime. Energy consumption of interior renovation over the residential model lifetime was found to be statistically the same; updated mean value of 370 GJ compared to 320 GJ estimated from figure given in the study. Although there is an increase of 15% in the calculated mean when results are revised for lifetime, the results were within the range of expected results given by the 90% confidence interval. Since similar materials were used in both residential building analyses, the results are in support of each other. Revised energy consumption ratio of selected interior finishes compared to life cycle energy consumption of the model yield 2.3% and 5.8% for regular and low-energy homes respectively, which are also in accordance with results found in this study.

4.3.7 Trends in residential building lifetime

Each American Housing Survey contains information regarding the mean age of demolished buildings. The procedure described in Chapter 4.2.1.1 was applied to past surveys. Results given in Figure 11 show an almost linear increasing trend in the mean age of demolished residential buildings in the last decade.

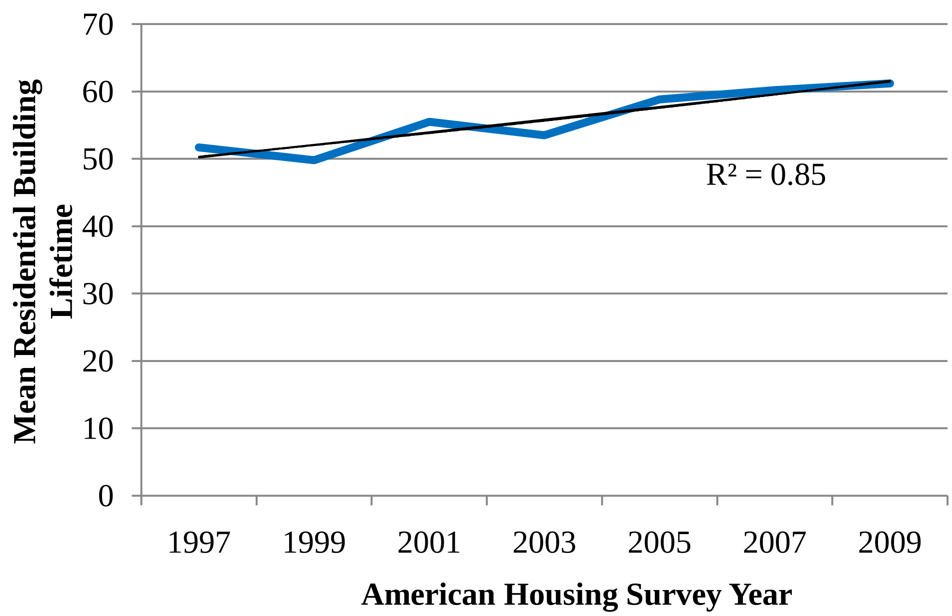


Figure 11. Change in U.S. residential building lifetime in the last decade (Census 1997; Census 1999; Census 2001; Census 2003; Census 2005; Census 2007; Census 2009; Nicholson 2009)

However, the observed linear increasing trend cannot continue indefinitely and there is expected to be an upper limit to achievable residential building lifetime dictated by structural design requirements or future technological improvements and demands. A model to predict trends in residential building lifetime is intended to be a future study.

4.3.8 Global warming potential of interior finish products over varying residential building lifetimes

The actual lifetime for which the residential building will be in use cannot be accurately known in most cases. Still, the constructor or the homeowner may have a good estimate for actual lifetime of the structure in some cases. In that case, it is both economically and environmentally preferable to make material selections by considering lifetime. Figure 12 presents life cycle greenhouse gas emission of interior finishes due to renovation. The assumption that finishes are replaced with the same type of product was also used in this scenario. For a known residential building lifetime, Figure 12 can be used to estimate greenhouse gas emissions of individual interior renovation products over the life cycle of the building. Using residential building lifetime as an independent variable when comparing multiple products facilitates identifying incidence points, significant points beyond which different conclusions can be drawn for products.

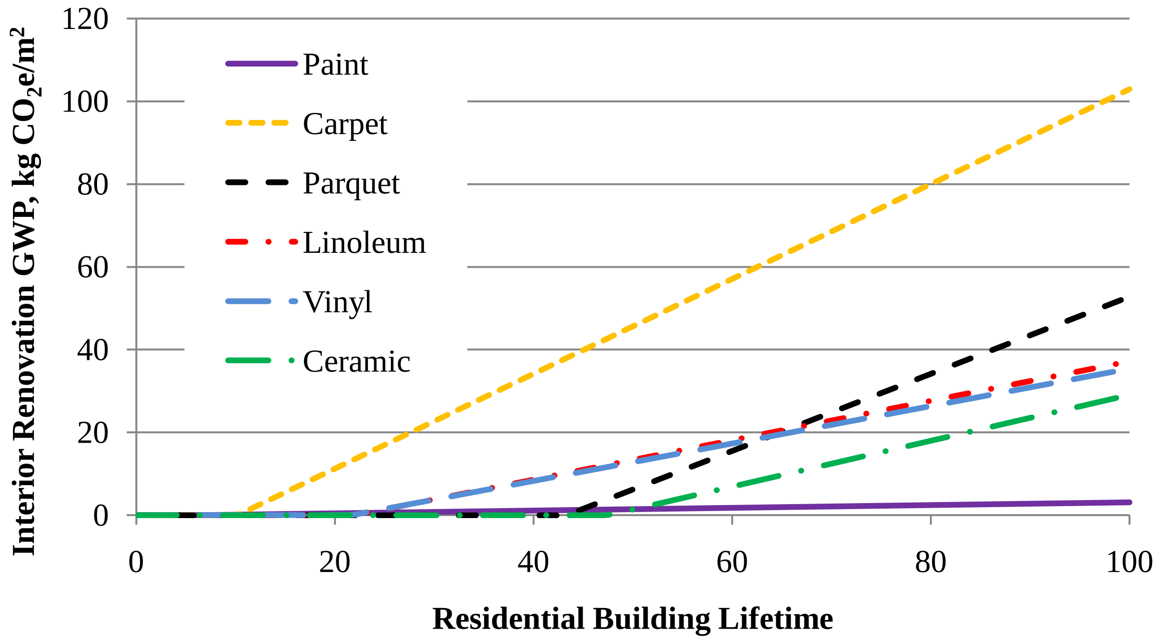


Figure 12. Global warming potential of interior finishes for different residential building lifetimes

Results are for renovation emissions only and do not include initial application of finishes. Interior finishes such as ceramic and hardwood on average do not require renovation until year 45, whereas paint and carpet need to be replaced several times by that time. The difference in greenhouse gas emissions of vinyl and linoleum are negligible regardless of residential building lifetime. An incidence point occurs at year 65, where greenhouse gas emissions from hardwood exceeds emissions from vinyl and linoleum. Based on these results, use of hardwood flooring has lower emissions until 65 years of residential building lifetime, after which will likely have higher emissions compared to vinyl and linoleum. Therefore, if building lifetime is known during design phase, material selections can be modified to decreases environmental footprint of the building. However, conclusions from Figure 12 should not be taken as definitive since shown trends have inherent uncertainties. More accurate data for both lifetime and emissions are necessary to improve results.

4.4 SUMMARY

Residential building lifetime data that presents existing trends in the U.S. was analyzed. Results indicate that residential building lifetime in the U.S. is currently 61 years. Existing LCAs rely heavily on estimates for residential building lifetime, and choices are usually made arbitrarily. This study is the first time mean residential building lifetime has been calculated from a large, reliable sample and used in LCA.

Lifetime of buildings and products presented in the current study should not be taken as static values. Future trends, occupant behavior, population demographics, regulatory policies, or development of new technologies have the potential to alter both lifetime and emissions of buildings and building products. The increasing trend in the age of demolished residential buildings was demonstrated in the current study. Ranges of values supported by statistical analysis were used throughout the study to compensate for some of the uncertainties associated with variables. The use of distributions that are based on past reported values, instead of deterministic values chosen arbitrarily for lifetime of buildings and building products improves the objectivity of a life cycle study that assumes average conditions when project specific data are not available. More data on environmental emissions of interior finishes is also a necessary step towards more robust results.

Interior renovation energy consumption for the residential model that was developed by using average U.S. conditions was found to have a mean of 220 GJ over the life cycle of the model. Using published data on energy consumption during pre-use and use phase of residential buildings enabled comparisons to be made among interior renovation impacts and other life cycle phases. Ratio of interior renovation to pre-use energy consumption was calculated to have a mean of 34% for a model regular home and 22% for a low-energy home. Ratio of interior renovation to life cycle energy consumption of residential buildings was calculated to have a mean of 3.9% for a model regular home and 7.6% for a low-energy home.

Life cycle impacts of regular buildings are dominated by use phase emissions. However, this is likely to change as buildings become more energy efficient during their use phase. An increase in the number of low-energy buildings would decrease the use phase emissions of residential buildings, increasing the relative importance of interior renovation over the life cycle of a residential building. Such an increase would necessitate more focus on interior finishes in a building LCA.

Due to its influence on product lifetime and emissions, the effects of consumer behavior related to interior finishes needs to be better quantified in order to improve accuracy of residential building LCA. Since lifetime information plays an important role in life cycle studies, and since consumer behavior can greatly influence product lifetime, developing a model that can accurately predict product lifetime by including the effects of technical factors as well as consumer behavior becomes a necessity. Such a tool would not only improve the accuracy of building LCA studies, but also of product comparison studies as well. This subject is discussed in detail in Chapter 5.

Without fully understanding and quantifying the underlying problems, it is not possible to develop effective environmental impact reducing strategies for the built environment. While collecting data for product lifetime, it was noticed that a product's actual lifetime was usually different than what the product was designed for, and was determined by the effects of consumer behavior. Therefore, studying the supply chain from the initial design phase down to individual consumer preferences could open new opportunities to reduce the environmental footprint of products and still maintain economy. This topic is further discussed in Chapter 6.

5.0 SERVICE LIFE PREDICTION OF RESIDENTIAL INTERIOR FINISHES FOR LIFE CYCLE ASSESSMENT

5.1 INTRODUCTION

The construction industry and the built environment are two key areas to achieve true sustainable development form an environmental, economic, and societal perspective. The sheer size of the construction industry and the dependence of other industrial sectors on the built environment makes them critical for the social and economic development of countries. However, the built environment is also a primary source of environmental impacts, not just due to the initial construction phase, but also from emissions occurring during the use phase to provide comfort and serviceability to occupants. The existing building stock requires continuous investments for repair and renovations, which increases life cycle impacts (Hovde 2004).

Life cycle assessment (LCA) is a tool that can quantify the environmental impacts of products, processes, and also buildings (Optis 2010). However, many building LCA studies do not adequately address service life, the period for which the product is actually in use, for buildings and building products but rather assume typical values, e.g. 50 years for residential building lifetime (Adalberth 1997a; Winther 1999; Keoleian 2001;

Thormark 2002). Such assumptions for building and building product lifetimes introduce additional uncertainty into the study and have the potential to alter results.

Compared to the structural frame or permanent components of a building, interior finishes including but not limited to paint or floor covering are replaced more frequently over the life cycle of a building, and potentially have significant environmental impacts. Lifetimes of interior finishes are affected by consumer behavior to a much higher degree compared to permanent components of a building, such as roofing or insulation. Therefore, it is vital to accurately estimate service life of interior finishes in an LCA study. This study proposes a tool to estimate service life of products that are affected by consumer behavior.

Knowledge about expected service life of building products is a key component for sustainable construction, as well as maintaining infrastructure assets (Lacasse 2008). Asset managers are responsible for a significant amount of construction and maintenance work. Costs accrued during the use phase of a building may be comparable to or even exceed initial design and construction costs (Chown 1996). Service life prediction of building products offers great benefits for facility managers in terms of providing a means of foreseeing future expenditures related to renovation. The ability to predict future expenditures would reduce budgetary pressures and would also allow construction work to be scheduled accordingly. Service life is a key metric that is utilized for economic decision–making for return on investment or investment planning for maintenance (Moser 2002).

This section addresses a gap by modifying the commonly accepted service life prediction method, namely, the Factor Method, to determine service life of building products that can be used within LCA. Statistical use of published lifetime data that inherently includes both social and technical factors that influence lifetime would improve the reliability of calculated service life estimates. Including accurate lifetime information into LCA allows a better understanding of life cycle impacts, ultimately enhancing the accuracy of LCA studies. The discussions herein were supported by examples for residential interior finishes.

5.1.1 Service life prediction and LCA

For building products, lifetime has the potential to influence LCA results and even alter the results of product comparison studies. The extended use duration of buildings and building products compared to daily consumable products necessitate that service life be taken into account during analysis. Therefore, reliable data on service life of building products would improve LCA results (Strand 1999).

Due to lack of service life data and a systematic method to predict the service life of interior finishes, LCA practitioners rely on limited data, or use arbitrary product lifetimes in their analyses. In addition to providing a more engineered approach to the problem of service life prediction, the proposed method and results calculated for interior finishes would also find applications within building LCA. LCA and service life prediction can be used in conjunction to identify and optimize service life and environmental impacts of building products (Hovde 2004).

5.1.2 Existing Service Life Prediction Methods

As suggested by Masters and Brandt (1987), service life prediction methods should be generic enough to be applicable to a wide range of materials, should clearly state their boundaries and document assumptions, and should guide users for interpretation of results. In addition, service life predictions need to be made by using standardized methods to ensure objective and comparable results (Frohnsdorff 1996). There are different approaches to service life prediction that can be grouped under four categories, each having unique applications and limitations: analytical models, statistical models, empirical methods, and experimental methods (Shohet 2004).

The analytical models proposed by various researchers to estimate service life of building products or components include predictive equations to estimate deterioration progress of building materials, methods that use Markov chains or Laplace transformation of time dependent variables, computer programs that use adaptive importance sampling and fault tree analysis (Hovde 2004). Statistical models that predict the amount of deterioration based on data from laboratory test results were also proposed. However, unless a large dataset is available, the use of a purely statistical approach may not be the best approach (Rudbeck 1999). The Factor Method originally developed by the Architectural Institute of Japan and later adopted by International Organization for Standardization (ISO) standard 15686 for service life prediction is an example of an empirical method. The lifetime of a product can also be determined experimentally by testing for expected in-use conditions or unfavorable conditions for accelerated testing (Shohet 2004). Daniotti and Cecconi have published a state-of-the-art report on test methods for service life prediction having a focus on accelerated laboratory test procedures and their correlation to service life data (Daniotti 2010).

The two American Society for Testing and Materials (ASTM) standards on statistical analysis of service life data, namely, ASTM G166 and ASTM G172, provide guidance on estimating service life of products when an adequate sample size has been obtained through testing, either under normal conditions, or in an accelerated test setup (ASTM 2003; ASTM 2005). The two standards were not developed for service life prediction and are more suited towards lab testing of products to obtain lifetime distribution curves. However, a detailed description was presented for a statistical procedure to define service life distributions from lifetime data, which was used in this study.

Although there are a multitude of different methods and approaches, the existing trend in service life estimation has been to focus on material durability as a means of estimating service life (Sjostrom 2001; Hooper 2002; Sjostrom 2002; Shohet 2004; Lacasse 2005; Shohet 2006). This represents a purely technical approach, where subjective behavior of consumers is excluded. Although such a technical approach may be valid for structural frame of a building, it is limited in scope for interior finishes where the effects of consumer behavior may influence product lifetime to a much higher degree.

Among the listed methods, the Factor Method stands out as a versatile tool that can incorporate the effects of consumer behavior to assess service life. In addition, the method has been adopted by ISO 15686 for service life prediction. Another contributing factor was that LCA, also described by the same international standardization organization (under ISO 14040), would be a primary area for application of results.

Existing service life prediction studies focus on structural frame elements such as concrete, steel, and wood, or on external building components such as roofing or insulation (Pommersheim 1985; Abu-Tair 2002; Lacasse 2004; Daniotti 2010). Building products that are replaced more frequently, therefore having the potential of higher environmental impact over the life cycle of a building, currently lack viable service life research results. The goal of this research question was to integrate existing techniques, standards, and reports and apply them to residential interior finishes to estimate service life that can then be used to improve LCA studies.

5.1.3 Factor Method

In ISO 15686, the Factor Method is defined as a way of bringing together various factors that influence service life of products in order to make lifetime estimates. The purpose of the Factor Method is to provide an estimate of service life, which is different than service life prediction. By definition, estimated service life is calculated for a set of specific in-use conditions, whereas predicted service life is recorded past performance which should ideally be equal to the reference service life used during calculations (ISO 2000; Davies 2004; Hovde 2004; Lacasse 2004).

In order to estimate service life using the Factor Method, the reference service life of a product is multiplied with coefficients that are assigned to factors A through G given in Equation 4 (see Table 12 for definition of factors). A coefficient of 1.0 is assigned to factors that are found to not influence service life. Coefficients can be increased or decreased according to the specific application in comparison to the reference case. Conditions that should be considered while assigning coefficients to residential interior finishes have also been presented in Table 12. According to ISO 15686, the user is free to choose a suitable coefficient for factors that affect service life. Although a range of values for factors was not stated in ISO 15686, an example service life prediction of window frames uses a range of 0.8-1.2 for factors. However, this should not be taken as a limiting range by any means. Product specific guidelines have not been developed until now due to the complex nature of the problem (ISO 2000). Selection of a suitable starting point, the reference service life, is thus crucial to obtain reliable results.

$$ESLC = RSLC \times A \times B \times C \times D \times E \times F \times G \qquad \textbf{Equation 4.}$$

where *ESLC* is estimated service life of a component or product, and *RSLC* is reference service life of a component or product.

In the comprehensive state-of-the-art report by Hovde and Moser (2004), estimation of reference service life has been identified as a topic that needs improvement. Establishing reference service lives for commonly applied residential interior finishes has been one of the outcomes of this study.

Table 12. Definition of factors and their relation to residential interior finishes (Masters 1987; ISO 2000; Marteinsson 2003)

Agents	Factors	Conditions relevant to residential interior finishes
Inherent quality characteristics	A – Quality of components	Manufacture, storage, transportation phases
	B – Design level	Sub-layer, physical incompatibility
	C – Work execution level	Level of workmanship
Environment	D – Indoor environment	Biological factors, condensation, sustained or random stress
	E – Outdoor environment	Solar radiation
Operation conditions	F – In-use conditions	Occupant demographics, wear and tear
	G – Maintenance level	Quality and frequency of maintenance/cleaning

ISO 15686 requires service life estimations to be given with an 80% confidence interval (ISO 2000). The use of confidence intervals facilitates interpretation of the reliability and accuracy of results and provides a more statistical approach to the method. However, the current form of the method, where the user assigns deterministic coefficients to each factor affecting lifetime would not produce meaningful results since reliable probability distributions cannot be setup from a single value assigned to a factor. Therefore, the use of confidence intervals together with deterministic values would create a false sense of accuracy in lifetime estimates (Marteinsson 2003). Statistical distributions were defined and used for reference service life calculations in this study. Distributions defined from multiple data points allowed the use of an 80% confidence interval as suggested by ISO 15686.

Applications of service life prediction techniques, and of the Factor Method in specific, have been fairly limited. One aspect that limits the use of the method is a lack of knowledge of the tool and its capabilities by potential practitioners such as architects, consultants, building owners and managers (Hovde 2004). Additionally, the current deterministic approach gives too much independence to users and is another barrier preventing the widespread use of the method. Accurate and reliable results cannot be obtained by using the Factor Method in its current form. These shortcomings of the Factor Method have been improved in this study by the use of statistical distributions, in addition to determining reference service life by including the effects of consumer behavior as an additional factor.

5.1.4 Impact of consumer behavior on service life

Product service life is affected by two categories: durability related factors, and social and economic factors (Cooper 2004; Nicastro 2005). Products may be replaced due to failure or poor performance, as in the case when a painted surface fades excessively or starts to blister or peel. On the other hand, some durable products that are functioning well from a technical standpoint could also be replaced due to social and economic factors, such as when an occupant wishes to change the color or tone of a painted surface. The existing Factor Method successfully captures factors related to durability, but excludes the effects of social factors and occupant behavior.

Service life of building products are seldom determined by their durability (Hovde 2004). Research on repair projects have found that only 17% were initiated due to deterioration (Marteinsson 2005). The subjective perception of a building was identified as the main cause in 44% of renovations. Other contributing factors were change in use and change in economic circumstances with 26% and 13%, respectively. Therefore, the reference service life of a building product cannot be solely based on its design life or technical properties. The effects of consumer behavior, which is not currently covered within the Factor Method has significant influence on product service life (Gaspar 2008).

5.2 METHODS

The proposed method is a hybrid approach combining the statistical procedure outlined by ASTM G166 to define reference service life distributions, together with the use of triangular distributions to define factors that influence lifetime given by ISO 15686. Using a range of values or a distribution to define coefficients instead of deterministic values is a necessary step towards improving the reliability of results obtained from the Factor Method (Aarseth 1999; Moser 1999; Moser 2002). A triangular distribution defined by a minimum, maximum, and the most expected value is suggested. The straightforward form of a triangular distribution provides an advantage for the interpretation of results by users that may be from a wide range of backgrounds. In addition, when distributions are defined based on judgment or experience of the user, the use of more complex distributions may be unnecessary from a practical point of view.

The proposed method decreases the range of coefficients necessary for modifying factors, thus decreasing the sensitivity of results to variations assigned to each factor by different users. For building products that are used for extended durations, choosing a suitable starting point: a reference service life based on average practices that take the effects of consumer behavior into account, becomes a crucial first step in lifetime estimations.

Data sources used to demonstrate examples for interior finishes together with the procedure used to define distributions were described in this section. A hypothesis test conducted to verify the relationship between calculated service life and the probability of renovation was also described.

5.2.1 Data Sources

Multiple data sources were used to collect information on service life of interior finish products. Lifetime values suggested by trade associations as well as values used in peer-reviewed journal articles were used as data points in the current study. The fact that the majority of research papers found to contain product lifetime information were related to LCA signifies that service life prediction and LCA are interconnected and can be used together to improve the reliability of results.

Design lifetimes and product guarantee durations published by manufacturers were not included into the dataset. Lifetime data based on actual service life was used to define distributions. Published service life data that was obtained through analysis of an existing building or obtained through informal communications with manufacturers were used. Although several arbitrary data points that were logically supported by other facts may have also been included, purely arbitrary data points that were not reliable were not included into the dataset.

Actual service life of products inherently includes the effects of consumer behavior as well as technical criteria or durability. Therefore, the proposed method incorporates the effects of consumer behavior into reference service life calculations, and thus into the results of the Factor Method.

5.2.2 Products Investigated

Service life prediction of products should be differentiated according to type of building. Residential and commercial buildings have different occupant demands and renovation cycles. Residential buildings have been proposed to have a renovation cycle of 20-50 years, whereas the interval decreases to 10-20 years for offices and 5-10 years for department stores (Anderson 1999). Industrial buildings also have different occupant needs depending on the type of industry. In addition to the design life and durability of interior finishes, the building type also determines service life and therefore cannot be disregarded when making lifetime estimates.

Interior finish products that are commonly applied within residential buildings were investigated. Interior building paint, together with multiple flooring alternatives were studied. Table 13 provides the list of interior finishes studied, data points, and their sources. Some sources indicated that hardwood flooring was expected to last as long as the building itself, therefore not necessitating any interior renovation (Seiders 2007). Due to the large uncertainty associated with predicting building lifetime, the lower lifetime limit was selected, i.e. 50 years was used when lifetime was given as 50 or more years. The average was used when a range of lifetime values was given.

A clash between provided data and published statements by other researchers should be seen as an additional motivation for this study. The structured approach presented in this study should be regarded as an improved approach over using arbitrary lifetimes for buildings and building products, whose examples from published journal articles has been demonstrated above and in Chapter 4.1.1.

ASTM G166 requires a minimum of 10 data points in order to properly fit a distribution (ASTM 2005). This criterion was adhered to in this study as well. Reliable lifetime data for interior finishes were not readily available in large quantities. Therefore data points were collected from multiple sources for each product.

Table 13. Data points for lifetime of interior finishes

Interior finishes	Lifetime in years, (source)
Paint	3 (NYC), 4 (Lippiatt 2008), 5 (Scheuer 2003; Kelly 2007), 7 (Pullen 2000), 8 (Mithraratne 2004), 10 (Adalberth 1997a; Hed 1999; Fay 2000; Keoleian 2001), 15 (Seiders 2007)
Carpet	5 (Gunther 1997; Anderson 2002), 8 (Potting 1995; Keoleian 2001), 8-10 (Seiders 2007), 9 (Petersen 2004), 10 (Pullen 2000), 11, 15 (Lippiatt 2008), 12 (Scheuer 2003; Mithraratne 2004), 17 (Adalberth 1997a)
Linoleum	5-40 (Paulsen 2003), 7-40 (Gunther 1997), 15 (Potting 1995), 15-22.5 (Petersen 2004), 20 (Costmodelling; Gorree 2002), 25 (Jonsson 1997; Jonsson 1999; Seiders 2007), 30 (Lippiatt 2008)
Vinyl	7-40 (Gunther 1997), 8 (Potting 1995), 9, 23 (Petersen 2004), 17 (Mithraratne 2004), 18 (Scheuer 2003), 20 (Jonsson 1997; Jonsson 1999; Pullen 2000; Keoleian 2001; Paulsen 2003), 40 (Lippiatt 2008), 50 (Seiders 2007)
Hardwood	10 (Nebel 2006), 20 (Anderson 2002; Nebel 2006), 25 (Nebel 2006), 40 (Jonsson 1997; Jonsson 1999), 45 (Scharai-Rad 2002; Petersen 2004), 50 (Adalberth 1997a; Mithraratne 2004; Nebel 2006), 50+ (Gunther 1997), 100+ (Seiders 2007)

Notes: The sign '+' after a number indicates that expected lifetime was more than the given value.
Multiple references after a data point indicate multiple occurrences in different studies.

5.2.3 Distributions

The use of distributions to model variables enables a more elaborate analysis of events compared to arbitrarily choosing deterministic values. Statistically, multiple distributions can be used to represent data, but the selection should be based on how well the distribution fits existing data and whether it leads to logical projections when extrapolated beyond existing data (ASTM 2005).

Normal distributions are widely used to describe naturally occurring distributions. However, ASTM G166 advises caution when using normal distributions for service life data (ASTM 2005). The symmetrical shape of a normal distribution facilitates calculations and interpretation but creates a shortcoming for use on service life data since most distributions are skewed, not symmetric (ASTM 2005). The use of Weibull distributions were supported by other studies as well and was adopted in the current study (Lounis 1998; Rudbeck 1999; Marteinsson 2003; Jernberg 2004; Marteinsson 2005). In addition, Table 9 demonstrates that a Weibull distribution provides the best fit for the majority of lifetime variables.

There are two parameters necessary to define a Weibull distribution, namely shape and scale parameters, analogous to using mean and standard deviation to define a normal distribution. The statistical analysis method described in ASTM G166 was applied separately to each interior finish product to determine Weibull distribution parameters necessary to estimate service life based on actual conditions (ASTM 2005).

The original form of a Weibull distribution shown in Equation 5 can also be written as given in Equation 6. This is in the form of an equation describing a line, y=mx+n.

$$F(t) = 1 - e^{\left(t/c\right)^{b}} \qquad \textbf{Equation 5.}$$

where *F(t)* represents the probability that an interior finish would be replaced by time *t*. *t* is service life of products given in years; *b* and *c* are shape and scale parameters, respectively, necessary to define a Weibull distribution.

$$\ln\left[\ln\frac{1}{1-F(t)}\right] = b\ln(t) - b\ln(c) \qquad \textbf{Equation 6.}$$

The set of equations in the form given in Equation 6 would be solved for parameters *b* and *c* in order to calculate probability of renovation, *F(t)*. This creates a recursive problem which was overcome by using the median rank estimate given in Equation 7 to initially estimate *F(t)* (ASTM 2005).

$$F(t) = \frac{j - 0.3}{n + 0.4} \qquad \textbf{Equation 7.}$$

where *j* is the order of data points when the lifetime dataset is sorted in ascending order and *n* is the total number of data points in the dataset.

Since there are multiple data points for product lifetime, linear regression analysis was used to determine shape and scale parameters of a Weibull distribution. After a product-specific Weibull distribution has been defined, probability of renovation with respect to observed service life was plotted using the cumulative distribution function.

ISO 15686 also suggests an 80% confidence interval in estimated service life results (ISO 2000). This limit is set for maintainable components, which would apply to interior finishes. An 80% confidence interval was used in this study to determine the lower and upper bounds of reference service life estimates.

5.2.4 F-test hypothesis testing

Hypothesis testing is a statistical procedure to decide whether to reject or not to reject a hypothesis. In this study, hypothesis test was applied to determine whether the correlation between probability of renovation calculated from the dataset and the independent variable of product service life occurred by chance.

The term alpha is used to denote the probability of rejecting a true hypothesis; in this case concluding that there is no strong relationship when it is otherwise. A typical value of 0.05 was chosen for alpha.

The critical F value ($F_{critical}$) can be read from F-distribution tables by using the assigned alpha value together with degrees of freedom of the dataset (NIST 2010). If the calculated F value ($F_{calculated}$) greatly exceeds $F_{critical}$, then it is unlikely that strong correlation among variables occurred by chance. The probability of a higher $F_{calculated}$ occurring by chance (P-value) was also calculated.

5.3 RESULTS AND DISCUSSION

The proposed method has been applied to multiple interior finish products to determine reference service life that can be used in the Factor Method described in ISO 15686. Regression analysis has been used to determine the coefficients necessary to define Weibull life distribution for each product. These coefficients together with the resulting Weibull distributions are given in Table 14.

Table 14. Weibull life distributions of interior finishes

Interior finishes	Shape parameter, b	Scale parameter, c	Weibull life distribution
Paint	2.44	8.24	$F(t) = 1 - e^{-\left(\frac{t}{8.24}\right)^{2.44}}$
Carpet	2.92	11.4	$F(t) = 1 - e^{-\left(\frac{t}{11.4}\right)^{2.92}}$
Linoleum	4.71	24.3	$F(t) = 1 - e^{-\left(\frac{t}{24.3}\right)^{4.71}}$
Vinyl	2.23	25.3	$F(t) = 1 - e^{-\left(\frac{t}{25.3}\right)^{2.23}}$
Hardwood	1.88	48.4	$F(t) = 1 - e^{-\left(\frac{t}{48.4}\right)^{1.88}}$

Parameters and distributions in Table 14 should not be taken as definitive solutions. Reliable and publicly available sources were used in this study. Distributions were defined by using at least 10 data points. However, future research supported by a trade association, or involving a residential survey to determine product lifetime would be able to collect additional data points. The above given values are expected to change when such findings are incorporated into the existing dataset.

Figure 13 shows the cumulative distribution function of each interior finish. It can be used to determine the cumulative probability of renovation for a given service life. This data would find applications in the field of investment planning for buildings or in economic cost benefit analysis.

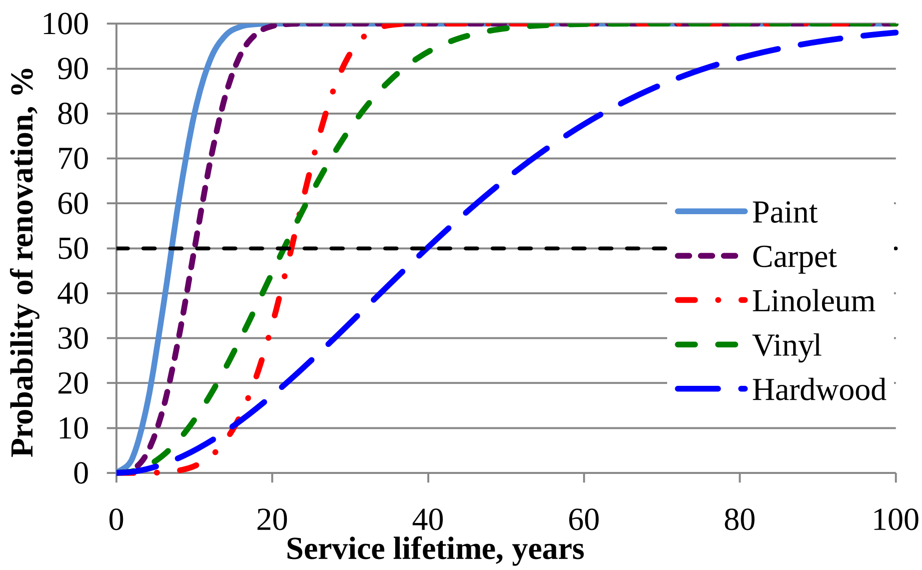


Figure 13. Probability of renovation cumulative distribution functions for interior finishes

Use of distributions enables a detailed analysis for estimating product lifetime. Especially when combined with the Monte Carlo method, distributions can provide a robust statistical analysis that cannot be captured with the use of deterministic values.

Statistical properties of a distribution could be reported to enhance interpretation of the variable. For normal distributions, the calculated mean point also corresponds to the midpoint, which also has the highest probability of occurrence. This is not the case for a Weibull distribution since probability distributions are not symmetric around the midpoint. Median service life of products can be estimated by drawing a horizontal line at the 50% probability of renovation in the cumulative distribution functions presented in Figure 13. Average service life of interior finishes estimated from the median of these distributions is given in Table 15. The 80% confidence interval required by ISO 15686 was used to locate upper and lower boundaries of the range of results. The given distributions or the corresponding average and range values can be used in the Factor Method for reference service life to depict real life conditions when analyzing residential buildings.

Table 15. Average service lifetime of interior finishes with an 80% confidence interval

Interior finish products	Lower bound (years)	Average service lifetime (years)	Upper bound (years)
Paint	3.3	7.1	12
Carpet	4.1	10	16
Linoleum	15	22	29
Vinyl	9.2	21	36
Hardwood	15	40	73

The guarantee period provided by the manufacturer may be the only indicator of design life for some products (Nicastro 2005). Paint products that are guaranteed for lifetime can be encountered in the market today. A painted surface must be kept under ideal conditions (e.g. low to no UV radiation, water damage, biological factors, wear and tear etc.) in order not to require repainting over the lifetime of the building. In addition to difficulties in achieving such conditions in real life, the influence of social factors on lifetime of products cannot be disregarded. A new or an existing occupant might wish to change the color or tone of a painted surface, even though the existing layer of paint may technically be performing satisfactorily. An average repainting interval of 7 years for residential buildings was presented in Table 15 based on reported past experience. The example for paint demonstrates the potential difference between actual service life and design life or guarantee duration provided by manufacturers. Using design lifetime as reference service life for interior finish products in the Factor Method would necessitate the use of a wider range of coefficients to account for real-life, average conditions. The use of theoretical reference service life combined with the need to use a larger range of coefficients increases subjectivity and decreases accuracy of results. The proposed method and examples presented in this study were based on average conditions and therefore provide a more reliable starting point for service life estimations.

Service life estimates have applications in various other fields including LCA studies, facilities management, or in an economic analysis for asset planning. When analyzing a building assuming average conditions, or in cases where detailed information may not be available, reference service life calculated based on average conditions could be used which would be equivalent to setting lifetime influencing factors equal to 1. However, when project specific data are available, the reference service life should be modified by coefficients described in ISO 15686. Triangular distributions, defined by a minimum, maximum, and an expected value can be used for each coefficient in the Factor Method. A Monte Carlo analysis would then provide the mean estimated lifetime together with a confidence interval, which would allow the user to interpret the reliability of results.

5.3.1 Hypothesis test

The F-test was applied as the hypothesis test to check the correlation between the interior finish service life data points as the independent variable, and the probability of renovation calculated from the dataset. $F_{calculated}$ values were found to be much higher than $F_{critical}$ values found from F-distribution tables, as shown in Table 16. The calculated P-values show the minute probability that results occurred by chance, indicating that there is a strong relationship between product service life and the probability of renovation distributions calculated in this study.

Table 16. F-statistic values for interior finishes

Interior finishes	$F_{calculated}$	$F_{critical}$	P-value
Paint	112	5.32	5.5×10^{-6}
Carpet	181	4.96	1.0×10^{-7}
Linoleum	93	5.3	1.1×10^{-5}
Vinyl	64	4.75	3.8×10^{-6}
Hardwood	129	4.6	2.0×10^{-7}

5.3.2 Actual life compared to design life

The proposed reference service lives are based on average use conditions and environments. They inherently include an average amount of unfavorable conditions observed in real-life. This needs to be taken into account when deciding on coefficients to calculate the estimated service life of a product. Unless it is known that the product would be used in a significantly different environment or use conditions compared to the average, the values of factors A-C and G may be taken as 1.0 as the coefficient for modifying factors in the Factor Method where a statistical approach is used. However, decisions for factors should be made specific to each product and application to ensure that all factors in Table 12 have been addressed in the analysis.

An added benefit of using actual life instead of design life as reference lifetime is that the user is required to make fewer assumptions regarding factors affecting lifetime. In addition, the chosen coefficients are limited to a narrower range. Both of these help reduce subjectivity of results.

An analysis involving hardwood flooring could use the 100+ years design lifetime as suggested by the National Association of Home Builders (Seiders 2007). However, average service life distribution shows that 50% of hardwood flooring is expected to be renovated within 40 years and the probability of flooring being used for 100 years is low. The 40 years service life estimated for hardwood flooring was based on existing practices. Although it is possible to modify the 100-year design life down to 40 years of actual use, the range of coefficients necessary to do so is larger than using actual lifetime as the reference service life. Furthermore, actual life calculated using distributions that are based on past experience inherently includes the effects of social factors that may be as important as durability for some products. It must be stressed that the effect of consumers may not be completely captured within the existing coefficients of the Factor Method, and that the proposed method would be a viable approach to overcome this problem.

5.3.3 Service life prediction results applied to residential building LCA

Estimating the service life of interior finishes presents an opportunity to apply results to the residential building LCA that was discussed previously in Chapter 4. Weibull life distributions presented in Table 14 were used instead of distributions shown in Table 8 to recalculate life cycle environmental impacts of interior renovation in Table 10.

An 80% confidence interval was used during recalculation by adhering to the ISO 15686 requirement, instead of the 90% confidence interval previously used to report results. Other than a difference in the upper and lower bounds of the expected range of results, the statistical properties of recalculated life cycle impacts of interior finishes presented in Table 17 are very similar to results presented in Table 10. The developed method presents a structured approach to estimating service life of products that can then be used directly in LCA studies as demonstrated here.

Table 17. Environmental impacts of interior renovation for the residential model by using the developed service life prediction method

	Lower Bound	Mean	Upper Bound	Coefficient of variation
Energy (GJ)	60	230	440	0.65
Global Warming Potential (t CO_2E)	3.0	11	21	0.65
Acidification (kg H+)	1.3	4.7	9.0	0.70
Eutrophication (kg N)	2.6	10	20	0.72
Smog (kg NO_x)	41	130	240	0.60

Note: Lower and upper boundaries are for an 80% confidence interval

5.4 SUMMARY

There is a need for service life prediction of building products both from industry and academia. Facility and asset managers would benefit from a greater ability to foresee and plan for future expenditures, and for economic decision-making to make informed decisions on investment planning. Researchers studying building LCA would be among those that can apply service life estimates in their analysis.

The Factor Method is the most promising method available to estimate service life of products. However, the current deterministic approach is an important barrier preventing the widespread use of the Factor Method. Objective and reliable results cannot be obtained by using the method in its current form. Without a systematic approach, applications of the Factor Method would be limited.

A hybrid method combining statistical procedures described in ASTM G166 with the Factor Method adopted by ISO 15686 was proposed. The proposed method has several advantages. Existing service life prediction models do not capture the effects of social factors on lifetime of products. However, for certain building product categories including interior finishes, the effects of social factors may be as important as durability. Excluding the effects of social factors reduces the accuracy and reliability of results. The proposed method inherently includes the effects of social factors in the dataset used to define lifetime distributions. Another advantage is that choosing reference service life based on real-life conditions decreases the range of coefficients necessary for modifying factors in comparison to when design lifetime is used, thus decreasing the subjectivity of results due to variations in assigned values by different users.

The proposed approach has been presented with example calculations for several interior finish products. The individual lifetime distributions of these products have been developed. Average estimated service life together with an 80% confidence interval was also presented. Reliable sources including peer-reviewed research articles were used to gather data. However, the need for further reliable data points must be stressed in order to improve the accuracy of coefficients used to define distributions. Since both the dataset used during calculations, and the resulting parameters of the Weibull distributions have been presented, it is possible to update distribution parameters given that additional data points are collected through a residential survey or through trade associations. Although the Weibull distribution parameters would differ somewhat, the overall method would remain the same. The proposed hybrid method can also be applied to other products that are studied within the Factor Method. Products whose lifetimes are influenced by the effects of social factors are prime candidates to apply this method.

6.0 STRATEGIES TO REDUCE DISPARITY BETWEEN DESIGN AND SERVICE LIFETIMES OF INTERIOR FINISHES: A QUALITATIVE APPROACH

The proposed strategies are discussed qualitatively in this chapter. The advantages and applicability of these strategies are explained. After stating how efficiency and environmental performance of interior finishes can be improved, the next steps would be to quantify these strategies. Quantification through analysis and eventual product realization are planned future research areas.

6.1 INTRODUCTION

For interior finishes, observed service life may be much shorter than design life, or manufacturer guarantee periods for some product categories. Although product failure caused by lack of durability is important, product obsolescence dependent on occupants also play a crucial role in product replacement decision (Ashworth 1996).

Early replacement decision of consumers, which determines service life affects life cycle environmental impacts of interior finishes, perhaps more so than choosing the product having the least emissions (Gunther 1997). Therefore, identifying factors that affect service life of commonly applied interior finishes and developing strategies to reduce the disparity between service and design life becomes an important focal point to reduce environmental emissions of buildings and interior finishes.

In order to correctly propose strategies to reduce the disparity between design and service lifetimes, it was necessary to identify causes that contribute to premature product replacement. A description of factors that lead to obsolescence of interior finishes was presented. Strategies designed specifically for interior finishes were proposed. The environmental and economic implications of suggested strategies have also been discussed.

6.2 BACKGROUND

6.2.1 Material consumption in the U.S.

Overall material consumption in the U.S. has increased considerably in the 20th century, from 2 metric tons per capita to 10 metric tons. Combined with an increase in population, this amounts to an increase of 19 times in total material consumption within a century. At the beginning of the 21st century, the U.S. was responsible for a third of global materials consumption and 20% of greenhouse gas emissions, with only 5% of global population (Dorf 2001; Fernandez 2006). Within a century, the percent weight of renewable materials consumed within the economy has decreased from 42% to 5%, not including fossil fuels. Therefore, the current economic structure and the related material consumption in the U.S. withdraws more than 95% of its resources from nonrenewable natural capital of the Earth (Fernandez 2006).

By 1999, global material consumption had already exceeded the carrying capacity of the Earth (Wackernagel 1999). The situation would only get worse as nations try to provide comparable amounts of commodities to their citizens as that of the U.S., by mimicking the U.S. industrial and economic model. Such an unsustainable trend could lead to catastrophic failure for the global society, environment and economy. It is of vital importance to reduce the current consumption level in the U.S. in order to set a sustainable model that other nations can implement.

The construction industry is responsible for one of the largest shares of material consumption and waste generation in many industrialized nations. Construction waste constitute 15-30% of municipal waste stream in the U.S. (Fernandez 2006). Buildings consume large quantities of materials throughout their lifetime. Implementing environmental principles to reduce consumption have the potential to reduce the national footprint (Fernandez 2006).

6.2.2 Building product lifetime

Different building components and products are designed for different lifetimes. The structural frame of a building would be expected to withstand stresses for a long time, up to a century in some cases, whereas the same cannot be said for interior finishes. Interior paint for example, cannot be manufactured to last as long as the building at a reasonable cost (Nicastro 2005).

Determining design life of a building product is difficult. Most manufacturers do not clearly state the design life of their products. A guarantee period provided by the manufacturer may be the only reliable indicator of design life. However, guarantees for interior finishes are usually tied to a set of stringent conditions, which reduces the number of product returns. With reduced risk of returns, companies may provide guarantees that are beyond the product design life. In addition, the duration a product has been on the market, and guarantees offered by competitors also affect guarantee decisions (Nicastro 2005).

Published design life of interior finishes should not be taken as definitive values that are valid in any condition. For interior paint, fading depends largely on solar radiation the surface is exposed to. Inevitably, a painted surface is exposed to more solar radiation in the southern part of the U.S. compared to the northern part. Therefore, even if accurate laboratory tests were conducted to determine the durability of paint against fading, the period until fading exceeds an acceptable threshold would still be dependent on region and application. Even in the same location, different communities accept different quality levels depending on economic and social acceptability factors, which adds to the disparity between design and actual lifetime (Nicastro 2005).

Design life of building products may be seen as the theoretical lifetime that would be achieved under ideal conditions, where no additional influences affect lifetime. This is rarely achieved in real life, and so actual product lifetime that includes uncertainties associated with consumer behavior plays a more important role for environmental studies quantifying building related impacts.

Factors that influence product lifetime can be grouped into three categories: failure, dissatisfaction, and change in consumer needs. Technical failure is related to the design and durability of a product. Dissatisfaction is dependent on styling and lifestyle changes. A change in consumer needs may occur when occupants have children or become elderly for example. There are additional factors that affect dissatisfaction of consumers such as: initial design, alternative products, a new product introduced into the market, a drop in the quality of existing product, social and economic trends, cost and applicability of repairs, occupant demographics including age, income, education level (Packard 1963; Butlin 1982; Keoleian 1993; Cooper 2004; Mont 2008).

Companies or industrial sectors may use planned obsolescence to foster replacement sales and company growth. In that case, the lifetime of a product would be predetermined during initial design, after which the customer would be expected to make a replacement purchase. Use of fashion trends or gradual functional enhancements result in existing products to be viewed as inferior to newer ones, therefore, creating a replacement desire, although the existing product may be technically functioning (Guiltinan 2009).

6.2.3 Environmental product design approaches

Multiple design strategies have been proposed to reduce environmental impacts of products and extend their lifetime. The commonly accepted approach to environmentally responsible product design method is Design for Environment (DfE). DfE is a systematic approach to design for the environmental performance of a product. For many products, the majority of life cycle impacts are inherently determined during product design phase. The following list provides general metrics that can be seen under the broader definition of design for environment (Keoleian 1993; Fiksel 1996; Billatos 1997; Dorf 2001; van Nes 2003; Giudice 2006; Mont 2008):

- Substitute hazardous materials with environmentally benign alternatives
- Reduce generated waste
- Reduce energy consumption
- Design for reliability
- Design for repair and service
- Design for upgrade
- Design for disassembly and easy removal
- Design for remanufacture
- Design for reuse
- Design for recycle
- Design for product attachment

- Design for variability

These design concepts are not mutually exclusive, and do not limit the application of other principles. Although there is adequate number of published literature on this topic, their application remains limited. While it is technically possible to produce more durable products, there are economic, social, and environmental factors that affect lifetime and should be considered during decision-making. Durability by itself should not be the only design goal but a balance should be sought among these variables (Mont 2008). Designing appropriately durable products should be a goal to reduce waste caused by designing products that greatly exceed their service lifetime (Keoleian 1993).

A limitation of these principles is their focus on individual life cycle phases of a product (Mont 2008). Life cycle assessment, which considers the entire life cycle of a product, should not be separated from DfE during the design process.

6.2.3.1 Business perspective

Developing green products does not necessarily have to contradict the economic interests of a company. Environmental interests could very well be aligned with economic interests. In recent years, investors have become interested in environmental and social performance of companies in addition to their economic performance with the expectation that these companies would outperform competitors who do not pay attention to their environmental or social impacts. As a result, socially responsible funds are growing at twice the rate of other mutual funds (Dorf 2001). Increased awareness on the consumer side creates a market opportunity for companies that reorganize their activities according to sustainable principles.

Activities of a corporation can be revised according to the steps for environmentally responsible corporations principles, which are also in accordance with DfE principles (Dorf 2001):

- Pollution prevention through eliminating waste
- Product stewardship by reducing life cycle impacts of a product
- Design for environment by addressing end-of-life recovery, reuse, and recycling of products during initial product design
- Implement clean technologies that have lower impacts

In reality, economics has a high priority in green product manufacturers as well. A survey among companies that publicized as having environmental concerns revealed that two thirds were willing to raise prices by 0.1%, where one third were willing to raise by 1%. Only a few were willing to raise prices by 5%, and none more than that. The conclusion was that companies would reduce emissions given that their actions do not increase cost (Lave 1996; Dorf 2001). Since the survey was conducted on companies publicized as having environmental concerns, it is hard to imagine regular manufacturers voluntarily accepting financial drawback. A different study by Dummett (2008) also identified cost and payback period as an important factor for business to implement environmental changes. A call for change must be made either by legislative organizations or by consumers in order to push companies towards environmentally responsible production of goods. Without legal or economic drivers, sustainable development cannot be achieved on its own based on consciousness of companies.

6.2.4 Environmental policies

Environmental regulations may reduce impacts by restricting certain emissions that occur during manufacturing, or encourage development of new products that have lower impacts. Regardless of the approach, environmental policies make changes to the existing market structure, either by supporting new, green products over their traditional counterparts, or by extending responsibility of companies from point of sale until disposal, therefore implementing a life cycle perspective. Companies thus need to realign their products to account for these changes.

A take back scheme for specific products or industries is an environmental policy that is currently being employed in various countries. In take back schemes, sold products remain as assets to a company, which provides incentives to design for lifetime and end-of-life (Mont 2008). Extended producer responsibility (EPR) transfers the responsibility of safely disposing the product at end-of-life back to the producer. The Waste Electrical and Electronic Equipment (WEEE) Directive of the European Commission for electronic products that requires electronic manufacturers to collect and safely dispose products at end-of-life is an example to EPR that is currently exercised (Dorf 2001; Bogaert 2008). An EPR policy for interior finishes has not been developed until now. However, introduction of a similar take back scheme together with reuse, recover, or recycling of materials was suggested to provide environmental benefits for flooring materials (Gunther 1997). A viable remanufacturing mechanism should have a sufficient amount of old products in the market, development of a trade-in network, low collection costs, sorting and storage infrastructure (Keoleian 1993).

Extended producer responsibility shift responsibility from consumer to the producer for the post-consumer phase of the life cycle of a product. Such a shift would act as a driver for producers to reconsider designs, materials, and systems they use to create their products. The main goal of this regulatory action is to reduce environmental impacts of products through encouraging redesign (Giudice 2006). Another advantage of EPR is the fostering of a life cycle thinking into the business model rather than only focusing on profit at point of sale.

Another potential approach to reduce impacts would be to support labeling organizations and mandate use of green products in governmental contracts. This is another way to stimulate companies to revise their product lines and encourage new green products and manufacturers (Mont 2008). Consumers are then given more option to voluntarily choose products that have less environmental impacts.

The New York Housing Maintenance Code is an example of a regulation that affects lifetime of interior finishes (NYC). Accordingly, rental apartments are required to be repainted once every three years. Such limitations on lifetime provide opportunities for manufacturers to reformulate their products, to maximize profit and reduce emissions at the same time. Designing and guaranteeing a product for lifetime may not be logical when it is known that the surface would be repainted every three years.

Environmental action can be separated as those having short-term and long-term goals. Governmental action would be successful in achieving short-term goals. However, too much governmental interference on markets could create public outcry in capitalist societies, which could undermine sustainability efforts by creating polarization among society. A more secure, long-term approach would be to educate the public on environmental problems and potential solutions, by demonstrating the impacts of their actions and decisions and presenting alternatives that they can implement. Developing alternative strategies or products are vital for success of any long-term goal.

6.3 SUGGESTED STRATEGIES

Two strategies have been proposed to reduce environmental impacts of interior finishes. Through identifying the needs of various consumer groups, manufacturers can regionalize their products to suit the needs of occupants and present alternatives according to the needs of demographic groups. Another approach would be to use DfE principles for interior finishes, especially designing for end-of-life of such products. Combined with a take back scheme for applicable products, such a strategy could provide strong benefits both in terms of reducing environmental impacts and also for increasing market share of companies through efficient use of assets and improved public image.

6.3.1 Demographic specific product development

Demographics play an important role in product obsolescence. Technologically or functionally inferior products can be sold at reduced prices to consumers having fewer demands. Therefore, a product that may seem obsolete to a consumer may still be acceptable for another. Demographics also play an important role in interior renovation cycles. Age, income, culture, and attained education level are some factors that affect consumer decisions on product choice and replacement.

6.3.1.1 Paint

Today, it is common to find paint with a variety of finish options, combined with a multitude of color alternatives in the U.S. paint market. Companies provide different guarantee durations for their products, ranging from 15 years to matching building lifetime, depending on the quality of base material used. Different pigments are added to obtain the desired color, which does not affect paint quality and thus guarantees. The quality of the base solvent determines the overall quality, provided guarantee period, and ultimately the cost of the product. Consumers then make a decision based on the desired type of finish, guarantee period, and budget constraints.

For the majority of applications, the decision is made without a consideration for the type of building and occupant demographics. A distinction between the types of building, whether it is residential, retail, corporate, or governmental should be made during product selection. Commercial buildings have different lifetimes and different interior renovation cycles compared to residential buildings. It is possible to further classify residential buildings into owner-occupied and rental units. If a rental residence is repainted every couple of years, for example after every move, then using higher quality paint that is guaranteed for lifetime may not be the best choice. The same argument holds for commercial spaces that require shorter renovation cycles to provide customer satisfaction. Similarly, senior citizen's residences could be expected to have different interior renovation cycles than young professional's residences, or families that have children. The use of high quality paint having classic tones could be preferred when repainting is not expected for extended durations. Uninformed consumers can make decisions that are not in their best interest. Consumers should be directed towards their actual needs by differentiating products towards different building applications.

Identifying consumer needs would allow products to be reformulated towards specific needs. Certain harmful pigments and chemicals used to extend design life and provide longer guarantee periods may be substituted, reduced or completely eliminated. Similar to food labeling, a legislation that would require paint manufacturers to explicitly state ingredients and their dangers would allow consumers to make informed decisions regarding the potential health impacts of products they choose.

Water-based paints generally emit lower VOCs compared to oil-based paints. The paint industry is transitioning from oil to water based paints. However, although water-based have lower VOC emissions, they contain other hazardous chemicals as preservatives and fungicides such as arsenic disulfide and formaldehyde (Kibert 2008).

Trying to extend design life indefinitely, independent from occupant needs does not bode well for the environment and the economy. As technology progresses, industries move towards personalized services that target well-defined groups or individuals. So far, the paint industry has been able to provide a diverse color selection to consumers, but has not distinguished their products for specific regions, building types, or demographic indicators.

6.3.1.2 Flooring

Flooring industry fares better compared to paint industry in terms of product diversity based on application areas. Major carpet manufacturers suggest different types and designs of carpet for different locations. Distinctions have been made between residential, corporate, educational, governmental, healthcare, hospitality, and retail institutions. Customers are also directed to choose sturdy products for heavy traffic areas, and warmness and comfort for residential spaces.

6.3.2 Designing for end-of-life of hardwood flooring

There are several DfE principles that are tied to the end-of-life phase of a product, namely: ease of disassembly, remanufacture, reuse, recycle. However, existing flooring alternatives are not designed for end-of-life and so become waste once they are removed.

Flooring products, and especially hardwood flooring can be designed for ease of disassembly and reuse. Modularity is another potential strategy that has already been applied on carpets. The ability to take apart and replace components that have worn out extends service life of other parts of the floor overlay. Interface Inc. is the leading manufacturer of modular carpet tiles. Their business model is based on a take back scheme after product use, which is then remanufactured into new products. Take back schemes may also be a viable approach for flooring alternatives and especially wooden flooring options, once they are properly designed for end-of-life removal and reuse.

There are existing hardwood floor applications where unused material has been collected from multiple sites and used together. Unused material may be a result of excess orders, or simply scrap parts that have not been damaged. As long as product dimensions and type of wood are the same, hardwood obtained from different locations can be applied together. Refinishing with a darker veneer would solve the problem of differences in tone. However, since this method is limited to new, excess hardwood, their applications remain limited.

Designing hardwood for disassembly at end-of-life or for modularity would create a new market for used hardwood flooring. Refinishing by using a darker veneer would be necessary to provide the desired quality. However, such a strategy would have significant environmental and economic benefits. Reusing products extends their lifetime, thus reducing the difference between design and service life and improves material efficiency. In addition, opening new markets by reaching customers that could not afford new hardwood flooring would provide an additional source of income to companies that are competing in a well-established market.

6.4 SUMMARY

There are various product design approaches that aim to reduce environmental impacts. DfE principles are the most widely acknowledged of such methods. However, their application has remained fairly limited for interior finishes. Using DfE principles as the basis for design, several strategies were proposed to decrease the disparity between design and service life of interior finishes.

Lifetime of interior finishes are dependent on multiple factors including technical, as well as those related to the effects of consumer behavior. Demographics play an important role in defining consumer attitudes towards interior finishes. In addition, the type of building, or application location also becomes important considerations for service life of interior finishes. However, adequate product differentiation by regionalization or by addressing the needs of different consumer groups was identified as an area that is lacking. Products can be reformulated to adjust for increased or decreased design life that is more correlated with service life. This would not only decrease environmental impacts through more efficient use of materials and reduced emissions, but also provide economic benefits through improved customer satisfaction.

Another strategy aimed at decreasing the disparity between design and service life would be to redesign for end-of-life, more specifically for easy removal and reuse, especially for applicable flooring alternatives such as hardwood. Similar to modularity introduced by carpets, a modular hardwood overlay could be dismantled, refinished, and reapplied, thus extended service life considerably. As long as product dimensions and type of wood were the same, refinished hardwood from different sources could be used together. This strategy would provide new markets by reaching consumers that could not afford a new hardwood floor. Thus, environmental initiatives would be supported by economic benefits, which should be one of the conditions of environmental strategies and policies for their successful adoption by industry.

The suggested strategies are a step towards reducing environmental impacts of commonly applied interior finishes. They can be applied relatively quickly, without resistance from the respective industries since they also align with their economic interests. Similar to other industrial sectors, the construction industry should expect legislative restrictions to reduce their environmental footprint in the near future. Companies that embrace change early on would have a competitive advantage when environmental restrictions are imposed.

7.0 CONCLUSIONS

Significant improvements are possible in the construction industry through implementing innovative ideas and products. LCA is an important tool to quantify environmental impacts of products and processes. The main objective of the dissertation was to improve the LCA method by quantifying the impact of lifetime on LCA results. Residential buildings and interior finishes were used as case studies for this purpose. Including precise lifetime data into LCA allows a better understanding of a product's environmental impact that would ultimately enhance the objectivity of LCA results.

Important results of the dissertation are summarized in this chapter. The subject is divided into subsections to ease interpretation. Future work and recommendations section includes guides for researchers investigating similar research topics.

7.1 PULTRUDED FLAX FIBER REINFORCED COMPOSITE

Life cycle energy consumption of a pultruded flax fiber reinforced composite was analyzed and compared to a glass fiber reinforced composite. The novel aspect of this research was the pultrusion of a natural fiber together with a bio-resin. Natural fibers have been incorporated in composites for some time, although by other means of production. Pultrusion is one of the least energy consuming production methods for composites and so pultruding flax fibers together with a bio-resin has the potential to create an environmentally friendly composite.

Raw materials extraction and processing, transportation, manufacturing, and packaging phases were considered in the analysis. Embodied energy was also included into the analysis. NFRCs were found to consume 55-60% less energy compared to GFRC. Obtaining flax products from within U.S. presents opportunities to cut transportation impacts by half for NFRCs.

7.2 IMPACT OF LIFETIME ON U.S. RESIDENTIAL BUILDING LCA RESULTS

Residential buildings in the U.S. and commonly applied interior finishes were used to quantify the impact of lifetime on LCA results. Lifetime data that presents existing trends in the U.S. was analyzed as part of the study. Mean residential building lifetime was calculated from a large, reliable sample in this research. Results indicate that residential building lifetime in the U.S. is currently 61 years. A detailed statistical description of residential building lifetime has been presented therefore reducing the need to use arbitrary lifetime values in future LCA studies.

Range of values supported by statistical analysis was used throughout the study to compensate for some of the uncertainties associated with variables. The use of distributions instead of deterministic values improves reliability and makes results more objective.

Interior renovation energy consumption for the residential model that was developed by using average U.S. conditions was found to have a mean of 220 GJ over the life cycle of the model. Using published data on energy consumption during pre-use and use phase of residential buildings enabled comparisons to be made among interior renovation impacts and other life cycle phases. Ratio of interior renovation to life cycle energy consumption of residential buildings was calculated to have a mean of 3.9% for regular homes and 7.6% for low-energy homes.

Life cycle impacts of regular buildings are dominated by use phase emissions. However, this is likely to change as buildings become more energy efficient during their use phase, thus decreasing use phase emissions of a building and increasing the relative importance of interior renovation over the life cycle of a residential building. Such an increase would necessitate more focus on interior finishes in a building LCA.

7.3 SERVICE LIFE PREDICTION OF RESIDENTIAL INTERIOR FINISHES

There is a need for service life prediction of building products both from industry and academia. Existing guides and methods to estimate service life of building products have been investigated. The Factor Method is the most promising method available to estimate service life of products. However, the current deterministic approach is an important barrier preventing the widespread use of the Factor Method. Objective and reliable results cannot be obtained by using the method in its current form. Without a systematic approach, applications of the Factor Method would be limited.

A systematic, hybrid method for service life prediction that combines the effects of technical and social factors by using a statistical approach was proposed. The proposed hybrid method has several advantages. Existing service life prediction models do not capture the effects of social factors on lifetime of products. The proposed method inherently includes the effects of social factors in the dataset used to define lifetime distributions. Another advantage is that choosing reference service life based on real-life conditions instead of design life decreases the range of coefficients necessary for modifying factors, thus decreasing the subjectivity of results due to variations in assigned values by different users.

The proposed hybrid method can also be applied to other products that are studied within the Factor Method. Products whose lifetimes are influenced by the effects of social factors are prime candidates to apply this method.

7.4 STRATEGIES TO REDUCE DISPARITY BETWEEN DESIGN AND SERVICE LIFETIME OF INTERIOR FINISHES

There are various product design approaches that aim to reduce environmental impacts. DfE principles are the most widely acknowledged of such methods. However, their application has remained fairly limited for interior finishes. Using DfE principles as the basis for design, several strategies were proposed to decrease the disparity between design and service life of interior finishes. The suggested strategies are a step towards reducing environmental impacts of commonly applied interior finishes.

Product differentiation by regionalization or by addressing the needs of different consumer groups or demographics was identified as an area that is lacking in most types of interior finishes. Products can be reformulated to adjust for increased or decreased design life that is more correlated with service life. This would decrease environmental impacts through more efficient use of materials and reduced emissions.

Another strategy aimed at decreasing the disparity between design and service life would be to redesign for end-of-life, more specifically for easy removal and reuse, especially for applicable flooring alternatives. Similar to modularity for carpets introduced by Interface Inc., a modular hardwood overlay could be dismantled, refinished, and reapplied, thus extended service life considerably.

7.5 FUTURE WORK AND RECOMMENDATIONS

Impact of lifetime on LCA results was demonstrated for residential buildings in this study. Commercial buildings have different consumer demands and therefore different interior renovation cycles. The approach described in this study could be applied to commercial buildings to quantify impacts given that reliable lifetime data for buildings and building products specific to commercial buildings are found.

Multiple data points supported by statistical analysis were used throughout the study to compensate for uncertainties associated with variables. The use of distributions instead of deterministic values provides a range of results that improves reliability. However, data on environmental emissions of interior finishes was identified as a topic that needs to be improved. There is an urgent necessity for reliable data towards more robust results in building LCA.

The statistical distribution of U.S. residential building lifetime was presented. A linearly increasing trend for the age of demolished residential buildings was identified from past survey results. However, there is expected to be an upper limit to the achievable lifetime of a residential building, either dictated by structural factors or standards, or due to the effects of social factors. Further research towards identifying future trends in residential building lifetime would be effective to develop policies that target reductions in environmental impacts of residential buildings. Identifying an optimal average building lifetime could necessitate changes in existing building design procedures and standards.

The proposed service life prediction method has been presented with examples for several interior finish products. Reliable sources including peer-reviewed research articles were used to gather data. However, these values should not be taken as definitive values. Further reliable data points are necessary to improve the accuracy of coefficients used to define distributions. Since both the dataset used during calculations, and the resulting parameters of the Weibull distributions have been presented, it is possible to update distribution parameters given that additional data points are collected through a residential survey or through trade associations.

Typical range of values to assign for factors that influence service life of products needs to be developed. This can be achieved after a large-scale survey of existing buildings to identify the relative influence of factors with respect to each other for building products. This would further advance the applicability of the Factor Method.

Design strategies proposed in Chapter 6 that aims to reduce the disparity between design and actual lifetime of interior finishes can be realized relatively quickly and efficiently. The proposed strategies were discussed qualitatively in Chapter 6. Adequate technical knowledge and a fully developed market exist for interior finishes that were studied. Quantification through analysis and eventual product realization are planned future research areas.

APPENDIX

ENERGY LCI OF COMPOSITE ALTERNATIVES

A.1 ENERGY LCI OF FLAX FIBER COMPOSITE MADE BY USING 225 g/m^2 TYPE FABRIC

Mass and volume ratios need to be calculated based on known individual material densities, which are then used to compute the composite density.

	Density (g/cm^3)	Mass (%)	Mass (g)	Volume (%)
Flax, in Fabric form	0.69	29.6	0.33	48.5
Bio-Resin	1.36	53.4	0.60	44.1
Continuous Glass Fiber	2.57	17.0	0.19	7.4
Sum		100	1.13	100

Based on these values, $d_{composite}$ = 1.13 g/cm^3

Functional Unit = 1 cm^3 = 1.13 g

Transportation:

Glass Roves = 0.19 g @ 500 km = 0.12 kJ

Bio-Resin = 0.60 g @ 250 km =0.18 kJ

Flax Fibers: Assumed that flax was cultivated in France. Also, waste for converting flax fibers into flax fabric was assumed to be negligible.

From - To	Mode of transport	Dist (km)	Energy (kJ/0.33 g flax)
France – Port	Land - trucks	800	0.21
Port (France) – Port (India)	Sea	13,000	0.10
Port (India) – Weaving Facility	Land - trucks	2,800	0.72
Weaving Facility – Port (India)	Land - trucks	2,800	0.72
Port (India) – Port (U.S.)	Sea	24,000	0.17
Port (U.S.) – Pultrusion Facility	Land - trucks	800	0.21
Total		44,200	2.13

Total energy required for transportation = 2.43 kJ/cm^3

Raw Materials: → Glass Roves 48.3 kJ/g × 0.19 g/cm^3 = 9.2 kJ/cm^3

→ Bio-Resin 49.9 kJ/g × 0.60 g/cm^3 = 30.0 kJ/cm^3

→ Flax Fibers 9.55 kJ/g × 0.33 g/cm^3 = 3.2 kJ/cm^3

Total Energy for Materials = 42.4 kJ/cm^3

Manufacturing: → Electricity, 4.0 kJ/cm^3

Packaging: → LDPE Wrapping, 0.005 g LDPE × 78.9 kJ/g = 0.42 kJ

→ Timber Planks, 0.063 g wood × 0.3 kJ/g = 0.02 kJ

<u>Total Energy</u> = 49.2 kJ/cm^3

Energy demand for flax fiber composite made by using 225 g/m^2 type fabric.

A.2 ENERGY LCI OF FLAX FIBER COMPOSITE MADE BY USING 225 g/m^2 TYPE FABRIC OBTAINED FROM WITHIN U.S.

Functional unit same as before: Functional Unit = 1 cm^3 = 1.13 g

Transportation:

Glass Roves = 0.19 g @ 500 km = 0.12 kJ

Bio-Resin = 0.60 g @ 250 km = 0.18 kJ

Flax Fibers: 2,400 km by land-trucks = 1.0 kJ/cm^3

Total energy required for transportation = 1.3 kJ/cm^3

Raw Materials:

Glass Roves 48.3 kJ/g × 0.19 g/cm^3 = 9.2 kJ/cm^3

Bio-Resin 49.9 kJ/g × 0.60 g/cm^3 = 30.0 kJ/cm^3

Flax Fibers 9.55 kJ/g × 0.33 g/cm^3 = 3.2 kJ/cm^3

Total Energy for Materials = 42.4 kJ/cm^3

Manufacturing: → Electricity, 4.0 kJ/cm^3

Packaging:

LDPE Wrapping, 0.005 g LDPE × 78.9 kJ/g = 0.42 kJ

Timber Planks, 0.063 g wood × 0.3 kJ/g = 0.02 kJ

Total Energy = 48.1 kJ/cm^3 Energy demand for flax fiber composite made by using 225 g/m^2 type fabric, which is obtained from within U.S.

A.3 ENERGY LCI OF FLAX FIBER COMPOSITE MADE BY USING 685 g/m^2 TYPE FABRIC

Mass and volume ratios need to be calculated based on known individual material densities, which are then used to compute the composite density.

	Density (g/cm^3)	Mass (%)	Mass (g)	Volume (%)
Flax, in Fabric form	0.90	43.1	0.51	57.2
Bio-Resin	1.36	40.5	0.48	35.2
Continuous Glass Fiber	2.57	16.4	0.20	7.6
Sum		100	1.19	100

Based on these values, $d_{composite}$ = 1.19 g/cm^3

Functional Unit = 1 cm^3 = 1.19 g

Transportation:

Glass Roves = 0.20 g @ 500 km

= 0.12 kJ

Bio-Resin = 0.48 g @ 250 km

= 0.14 kJ

Flax Fibers: Assumed that flax was cultivated in France.

Also, waste for converting flax fibers into flax fabric was assumed to be negligible.

From - To	Mode of transport	Dist (km)	Energy (kJ/0.51 g flax)
France – Port	Land - trucks	800	0.32
Port (France) – Port (India)	Sea	13,000	0.15
Port (India) – Weaving Facility	Land - trucks	2,800	1.11
Weaving Facility – Port (India)	Land - trucks	2,800	1.11
Port (India) – Port (U.S.)	Sea	24,000	0.27
Port (U.S.) – Pultrusion Facility	Land - trucks	800	0.32
Total		44,200	3.27

Total energy required for transportation = 3.53 kJ/cm^3

Raw Materials:

- Glass Roves 48.3 kJ/g × 0.20 g/cm^3 = 9.4 kJ/cm^3
- Bio-Resin 49.9 kJ/g × 0.48 g/cm^3 = 24.0 kJ/cm^3
- Flax Fibers 9.55 kJ/g × 0.51 g/cm^3 = 4.9 kJ/cm^3

Total Energy for Materials = 38.3 kJ/cm^3

Manufacturing: → Electricity, 4.0 kJ/cm^3

Packaging:

- LDPE Wrapping, 0.005 g LDPE × 78.9 kJ/g = 0.42 kJ
- Timber Planks, 0.063 g wood × 0.3 kJ/g = 0.02 kJ

<u>Total Energy</u> = 46.2 kJ/cm^3

Energy demand for flax fiber composite made by using 685 g/m^2 type fabric.

A.4 ENERGY LCI OF FLAX FIBER COMPOSITE MADE BY USING 685 g/m^2 TYPE FABRIC OBTAINED FROM WITHIN U.S.

Functional unit same as before: Functional Unit = 1 cm^3 = 1.19 g

Transportation:

- Glass Roves = 0.20 g @ 500 km = 0.12 kJ
- Bio-Resin = 0.48 g @ 250 km = 0.14 kJ
- Flax Fibers: 2,400 km by land-trucks = 1.53 kJ/cm^3

Total energy required for transportation = 1.8 kJ/cm^3

Raw Materials:

- Glass Roves 48.3 kJ/g × 0.20 g/cm^3 = 9.4 kJ/cm^3
- Bio-Resin 49.9 kJ/g × 0.48 g/cm^3 = 24.0 kJ/cm^3
- Flax Fibers 9.55 kJ/g × 0.51 g/cm^3 = 4.9 kJ/cm^3

Total Energy for Materials = 38.3 kJ/cm^3

Manufacturing:

- Electricity, 4.0 kJ/cm^3

Packaging:

- LDPE Wrapping, 0.005 g LDPE × 78.9 kJ/g = 0.42 kJ
- Timber Planks, 0.063 g wood × 0.3 kJ/g = 0.02 kJ

Total Energy = 44.5 kJ/cm^3 Energy demand for flax fiber composite made by using 685 g/m^2 type fabric, which is obtained from within U.S.

BIBLIOGRAPHY

Aarseth, L. I., Hovde, P.J. (1999). Stochastic approach of the factor method for estimating service life. 8th International Conference on Durability of Building Materials and Components (DBMC), Vancouver, Canada, NRC Research Press.

Abu-Tair, A. I., McParland, C., Lyness, J.F., Nadjai, A. (2002). Predictive Models Of Deterioration Rates Of Concrete Bridges Using The Factor Method Based On Historic Inspection Data. 9th International Conference on Durability of Building Materials and Components (DBMC), Brisbane, Australia.

Adalberth, K. (1997a). "Energy use during the Life Cycle of Buildings: a Method." Building and Environment **32**(4): 317-320.

Adalberth, K. (1997b). "Energy Use During the Life Cycle of Single-Unit Dwellings: Examples." Building and Environment **32**(4): 321-329.

Agarwal, B. D., Broutman, L.J. (1990). Analysis and performance of fiber composites, John Wiley and Sons, Inc.

Anderson, J., Shiers, D.E., Sinclair, M. (2002). The green guide to specification: an environmental profiling system for building materials and components. Malden, MA, Blackwell Science.

Anderson, T., Brandt, E. (1999). The Use of Performance and Durability Data in Assessment of Life Time Serviceability. 8th International Conference on Durability of Building Materials and Components (DBMC), Vancouver, Canada, NRC Research Press.

Ashworth, A. (1996). "Estimating the life expectancies of building components in life-cycle costing calculations." Structural Survey **14**(2): 4-8.

ASTM (2003). G 172 - Standard Guide for Statistical Analysis of Accelerated Service Life Data. West Conshohocken, PA, ASTM International.

ASTM (2005). G 166 - Standard Guide for Statistical Analysis of Service Life Data. West Conshohocken, PA, ASTM International.

Ayres, R. U. (1995). "Life cycle analysis: A critique." Resources, Conservation and Recycling **14**: 199-223.

Bare, J. C., Norris, G.A., Pennington, D.W., McKone, T. (2003). "The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts." Journal of Industrial Ecology **6**(3-4): 49-78.

Bilec, M. (2007). A Hybrid Life Cycle Assessment Model for Construction Processes. Civil and Environmental Engineering. Pittsburgh, University of Pittsburgh. **Ph.D.:** 8-25.

Bilec, M., Ries, R., Matthews, H.S., Sharrard, A.L. (2006). "Example of a Hybrid Life-Cycle Assessment of Construction Processes." Journal of Infrastructure Systems **12**(4): 207-215.

Billatos, S. B., Basaly, N.A. (1997). Green technology and design for the environment. Washington, D.C., Taylor & Francis.

Bismarck, A., Aranberri-Askargorta, I., Springer, J., Lampke, T., Wielage, B., Stamboulis, A., Shenderovich, I., Limbach, H.-H. (2002). "Surface Characterization of Flax, Hemp and Cellulose Fibers; Surface Properties and the Water Uptake Behavior." Polymer Composites **23**(5): 872-894.

Bogaert, S., Van Acoleyen, M., Van Tomme, I., De Smet, L., Fleet, D., Salado, R. (2008). Study on RoHS and WEEE Directive, European Commission.

Borjesson, P., Gustavsson, L. (2000). "Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives." Energy Policy **28**(9): 575-588.

Bos, H. L. (2004). The Potential of Flax Fibres as Reinforcement for Composite Materials. Eindhoven, Eindhoven University of Technology**:** 1-11.

Bos, H. L., Mussig, J., van den Oever, M.J.A. (2006). "Mechanical properties of short-flax-fibre reinforced compounds." Composites: Part A **37**(10): 1591-1604.

Bowles, G., Gow, H. (1995). Sinking Funds for Major Repairs Provision: Some Calculated Examples, The Royal Institution of Chartered Surveyors**:** 139-144.

BPS High PerformancePC Broadloom Carpet. The Green Standard Environmental Product Declaration System. Industry, CA, Bentley Prince Street.

Butlin, J. (1982). Product Durability and Product Life Extension. Paris, France, OECD Publications.

Census (1997). 1997 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (1999). 1999 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (2001). 2001 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (2003). 2003 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (2005). 2005 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (2007). 2007 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (2009). 2009 AHS National Data, ASCII version. Washington, DC, Department of Housing and Urban Development, U.S. Census Bureau.

Census (2009). Table 1.1 - Introductory Characteristics. 2009 American Housing Survey. Washington, DC, U.S. Census Bureau.

Census (2009). Table 2-3. Size of Unit and Lot - Occupied Units. 2009 American Housing Survey. Washington, DC, U.S. Census Bureau.

Chown, G. A., Brown, W.C., Kyle, B.R., Lacasse, M.A., Vanier, D.J. (1996). Applying Service Life and Asset Management Techniques to Roofing Systems. Sustainable Low-Slope Roofing Workshop, Oak Ridge, Tennessee, Oak Ridge National Laboratory, U.S. Department of Energy.

Cooper, J. S. (2003). "Specifying Functional Units and Reference Flows for Comparable Alternatives." The International Journal of Life Cycle Assessment **8**(6): 337-349.

Cooper, J. S., Fava, J.A. (2006). "Life-Cycle Assessment Practitioner Survey." Journal of Industrial Ecology **10**(4): 12-14.

Cooper, T. (2004). "Inadequate Life? Evidence of Consumer Attitudes to Product Obsolescence." Journal of Consumer Policy **27**(4): 421-449.

Costmodelling Building Component Life Expectancy. Costmodelling Works. UK, Costmodelling Ltd.

Curran, M. A. (1996). Environmental life-cycle assessment. New York, McGraw.

Dahllof, L. (2004). LCA Methodology for Textile Products. Environmental Systems Analysis. Goteborg, Sweden, Chalmers University of Technology. **Licentiate of Engineering:** 1-37.

Daniotti, B., Cecconi, F.R. (2010). Test Methods for Service Life Prediction - State of the Art Report on Accelerated Laboratory Test Procedures and Correlation between Laboratory Tests and Service Life Data. W080 - Prediction of Service Life of Building Materials and Components, International Council for Research and Innovation in Building and Construction**:** 102.

Davies, H., Wyatt, D. (2004). "Appropriate use of the ISO 15686 -1 factor method for durability and service life prediction." Building Research & Information **32**(6): 552-553.

Davis, C. (2007). Integration of Life Cycle Analysis within Agent Based Modeling using a Case Study on Bio-Electricity. Energy and Industry Group. Delft, Delft University of Technology**:** 1-74.

Dhingra, R., J. Overly, et al. (2001). Environmental Evaluation Of Materials In New Generation Vehicles, Oak Ridge National Laboratory.

DOE (2009). 2009 Buildings Energy Data Book, Energy Efficiency & Renewable Energy, U.S. Department of Energy.

Dorf, R. C. (2001). Technology, Humans, and Society, Academic Press.

Dummett, K. (2008). Corporate Environmental Responsibility (CER). School of Architecture and Design. Melbourne, Victoria, RMIT University. **Ph.D.**

Durham, S. (2000, 01/03/2002). "New Flax Production Process Eyed." News and Events Retrieved September 30, 2009, from http://www.ars.usda.gov/is/pr/2000/000330.htm.

EIA Table B1. 2003 Commercial Buildings Energy Consumption Buildings (CBECS) Detailed Tables, U.S. Energy Information Administration.

EIA (2005). Table US1. Total Energy Consumption, Expenditures, and Intensities, 2005 - Part 1: Housing Unit Characteristics and Energy Usage Indicators. 2005 Residential Energy Consumption Survey--Detailed Tables, U.S. Energy Information Administration.

FAO (1990). Energy conservation in the mechanical forest industries. FAO FORESTRY PAPER 93 Rome, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS.

Fay, R., Treloar, G., Iyer-Raniga, U. (2000). "Life-cycle energy analysis of buildings: a case study." Building Research & Information **28**(1): 31-41.

Fernandez, J. (2006). Material architecture: Emergent materials for innovative buildings and ecological construction. Italy, Architectural Press.

Fiksel, J. (1996). Design for environment: creating eco-efficient products and processes. New York, McGraw-Hill.

Friedman, A., Callis, B. (2008). Table 16 - Year Building Built. New York City Housing and Vacancy Survey. New York, U.S. Census Bureau.

Frohnsdorff, G. J., Martin, J.W. (1996). Towards Prediction of Building Service Life: The Standards Imperative. 7th International Conference on Durability of Building Materials and Components, Stockholm, Sweden, E & FN Spon.

Gaspar, P. L., de Brito, J. (2008). "Service life estimation of cement-rendered facades." Building Research & Information **36**(1): 44-55.

Giudice, F., La Rosa, G., Risitano, A. (2006). Product Design for the Environment: A Life Cycle Approach. Boca Raton, FL, CRC Press, Taylor & Francis Group.

Gorree, M., Guinee, J.B., Huppes, G., van Oers, L. (2002). "Environmental Life Cycle Assessment of Linoleum." The International Journal of Life Cycle Assessment **7**(3): 158-166.

GREET (2009). Detailed California-Modified GREET Pathway for Liquefied Natural Gas (LNG) from North American and Remote Natural Gas Sources, California Environmental Protection Agency Air Resources Board**:** 1-46.

Guiltinan, J. (2009). "Creative Destruction and Destructive Creations: Environmental Ethics and Planned Obsolescence." Journal of Business Ethics **89**(1): 19-28.

Guinee, J. B., Heijungs, R., Kleijn, R., van der Voet, E., de Koning, A., van Oers, L., Elshkaki, A., Huele, R., Huppes, G., Suh, S., Sleeswijk, A.W. (2006). "Human and Ecological Life Cycle Tools for the Integrated Assessment of Systems (HELIAS)." The International Journal of Life Cycle Assessment **11**(Special Issue 1): 19-28.

Gunther, A., Langowski, H-C (1997). "Life Cycle Assessment Study on Resilient Floor Coverings." The International Journal of Life Cycle Assessment **2**(2): 73-80.

Hansen, A., M. Flake, et al. (2000). "Life cycle studies of renewable raw materials–natural fibre reinforced component and a varnish." Bioresource Hemp 2000: 13–16.

Hed, G. (1999). Service Life Planning of Building Components. 8th International Conference on Durability of Building Materials and Components (DBMC), Vancouver, Canada, NRC Research Press.

Hermans, M. H. (1999). Building Performance Starts at Hand-Over: The Importance of Life Span Information. 8th International Conference on Durability of Building Materials and Components (DBMC), Vancouver, Canada, NRC Research Press.

Hooper, R., Bourke, K., Ferguson, W.A., Clift, M. (2002). An Integrated Approach to Durability Assessment throughout Construction Procurement. 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia

Hovde, P. J., Moser, K. (2004). Performance Based Methods for Service Life Prediction - State of the Art Reports Part A & Part B. CIB W080 / RILEM 175-SLM Service Life Methodologies Prediction of Service Life for Buildings and Components, International Council for Research and Innovation in Building an Construction (CIB)**:** 95.

Huppes, G., de Koning, A., Suh, S., Heijungs, R., van Oers, L., Nielsen, P., Guinee, J.B. (2006). "Environmental Impacts of Consumption in the European Union." Journal of Industrial Ecology **10**(3): 129-146.

Interface Convert Design Platform by Interface FLOR. The Green Standard Environmental Product Declaration System. LaGrange, GA, Interface Inc. .

ISO (2000). ISO 15686-1:2000 - Buildings and Constructed Assets – Service Life Planning – Part 1: General Principles. Geneva, ISO.

ISO (2006). Environmental management - Life cycle assessment - Principles and framework, International Standard Organization.

Itard, L., Klunder, G. (2007). "Comparing environmental impacts of renovated housing stock with new construction." Building Research & Information **35**(3): 252-267.

Jernberg, P., Sjostrom, C., Lacasse, M.A., Brandt, E., Siemes, T., Haagenrud, S.E., Kucera, V., Odeen, K., Lewry, A., Schwarz, H-J., Yates, T., Grondin, G.Y. (2004). Guide and Bibliography to Service Life and Durability Research for Building Materials and Components. P. Jernberg, Lacasse, M.A., Haagenrud, S.E., Sjostrom, C.

Johnson, R., Kuby, P. (2003). Just the Essentials of Elementary Statistics, Thomson Learning Brooks/Cole.

Jonsson, A. (1999). "Including the Use Phase in LCA of Floor Coverings." The International Journal of Life Cycle Assessment **4**(6): 321-328.

Jonsson, A., Tillman, A-M., Svensson, T. (1997). "Life Cycle Assessment of Flooring Materials: Case Study." Building and Environment **32**(3): 245-255.

Joshi, S., L. Drzal, et al. (2004). "Are natural fiber composites environmentally superior to glass fiber reinforced composites?" Composites Part A **35(**3): 371-376.

Kececioglu, D. (1991). Reliability Engineering Handbook. Englewood Cliffs, N.J., Prentice-Hall.

Kellenberger, D., Althaus, H-J. (2009). "Relevance of simplifications in LCA of building components." Building and Environment **44**(4): 818-825.

Kelly, D. J. (2007). BRE, Design life of buildings - A scoping study. Glasgow, Scottish Building Standards Agency**:** 40.

Keoleian, G. A., Blanchard, S., Reppe, P. (2001). "Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House." Journal of Industrial Ecology **4**(2): 135-156.

Keoleian, G. A., Menerey, D. (1993). Life Cycle Design Guidance Manual: Environmental Requirements and the Product System. Cincinnati, OH, US Environmental Protection Agency.

Kibert, C. J. (2008). Sustainable construction: green building design and delivery. Hoboken, N.J., John Wiley & Sons, Inc.

Kijak, M., Moy, D. (2004). "A Decision Support Framework for Sustainable Waste Management." Journal of Industrial Ecology **8**(3): 33-50.

Kofoworola, O. F., Gheewala, S.H. (2008). "Environmental life cycle assessment of a commercial office building in Thailand " The International Journal of Life Cycle Assessment **13**(6): 498-511.

Koo, C. (2006). A study of the plastic life cycle assessment. Civil-Environmental Management, Universiti Teknologi Malaysia. **M.S.:** 81.

Korhonen, J. (2005). "Theory of Industrial Ecology: the case of the concept of diversity." Progress in Industrial Ecology - An International Journal **2**(1): 35-72.

Lacasse, M. A. (2008). Advances in service life prediction - an overview of durability and methods of service life prediction for non-structural building components. Annual Australasian Corrosion Association Conference, Wellington, New Zealand

Lacasse, M. A., Sjostrom, C. (2004). Recent advances in methods for service life prediction of building materials and components – an overview. CIB World Building Congress, Toronto, Canada

Lacasse, M. A., Sjostrom, C. (2005). Advances in Methods for Service Life Prediction of Building Materials and Components – Final Report – Activities of the CIB W80. 10th International Conference On Durability of Building Materials and Components (DBMC), Lyon, France

Lave, L. B., Matthews, H.S. (1996). "It's easier to say green than be green." Technology Review **99**(9): 69-69.

Lippiatt, B. C. (1999). "Selecting cost-effective green building products: BEES approach." Journal of Construction Engineering and Management **125**(6): 448-455.

Lippiatt, B. C. (2007). Building for Environmental and Economic Sustainability Technical Manual and User Guide. Gaithersburg, MD, National Institute of Standards and Technology.

Lippiatt, B. C. (2008). Building for Environmental and Economic Sustainability (BEES), The National Institute of Standards and Technology (NIST).

Lippiatt, B. C., Boyles, A.S. (2001). "Using BEES to select cost-effective green products." The International Journal of Life Cycle Assessment **6**(2): 76-80.

Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, J., Meil, J. (2004). "CORRIM: Life-Cycle Environmental Performance of Renewable Building Materials." Forest Products Journal **54**(6): 8-19.

Lounis, Z., Lacasse, M.A., Siemes, A.J.M., Moser, K. (1998). Further steps towards a quantitative approach to durability design Construction and the Environment - CIB World Building Congress, Gavle, Sweden

Marteinsson, B. (2003). "Durability and the factor method of ISO 15686-1." Building Research & Information **31**(6): 416-426.

Marteinsson, B. (2005). Service Life Estimation in the Design of Buildings - A Development of the Factor Method. Department of Technology and Built Environment. Gavle, Sweden, KTH Research School. **Doctoral Thesis:** 62.

Masters, L. W., Brandt, E. (1987). "Prediction of service life of building materials and components." Materials and Structures **20**(1): 55-77.

Miao, M. and N. Finn (2008). "Conversion of Natural Fibres into Structural Composites." Journal of Textile Engineering **54**(6): 165-177.

Mithraratne, N., Vale, B. (2004). "Life cycle analysis model for New Zealand houses." Building and Environment **39**(4): 483-492.

Moffit, B. (2009). Envirez Resin Overview, Ashland Chemicals Company.

Mohanty, A., M. Misra, et al. (2005). Natural Fibers, Biopolymers, and their Biocomposites, CRC Press.

Mont, O. (2008). "Innovative approaches to optimising design and use of durable consumer goods." International Journal of Product Development **6**(3/4): 227-250.

Moser, K. (1999). Towards the practical evaluation of service life – Illustrative application of the probabilistic approach. 8th International Conference on Durability of Building Materials and Components (DBMC), Vancouver, Canada, NRC Research Press.

Moser, K., Edvardsen, C. (2002). Engineering Design Methods for Service Life Prediction. 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia.

Mungkung, R. T., Udo de Haes, H.A., Clift, R. (2006). "Potentials and Limitations of Life Cycle Assessment in Setting Ecolabelling Criteria: A Case Study of Thai Shrimp Aquaculture Product." The International Journal of Life Cycle Assessment **11**(1): 55-59.

Nassen, J., Holmberg, J., Wadeskog, A., Nyman, M. (2007). "Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis." Energy **32**(9): 1593-1602.

Nebel, B., Zimmer, B., Wegener, G. (2006). "Life Cycle Assessment of Wood Floor Coverings." The International Journal of Life Cycle Assessment **11**(3): 172-182.

Ness, B., Piirsalu, E.U., Anderberg, S., Olsson, L. (2007). "Categorising tools for sustainability assessment." Ecological Economics **60**(3): 498-508.

Nicastro, D. H., Surovek, A.E. (2005). Defects, Deterioration, and Durability. Structural Condition Assessment. R. T. Ratay, John Wiley & Sons**:** 3-23.

Nicholson, K. (2009). Codebook for the American Housing Survey, Public Use File: 1997 and later. Fairfax, VA, U.S. Department of Housing and Urban Development**:** 1-14, 93, 128, 165.

Nicoletti, G. M., Notarnicola, B., Tassielli, G. (2002). "Comparative Life Cycle Assessment of flooring materials: ceramic versus marble tile." Journal of Cleaner Production **10**(3): 283-296.

NIST (2010). e-Handbook of Statistical Methods, NIST/SEMATECH.

NOAA (2010). "NOAA Satellite and Information Service." Retrieved July, 2010.

Norris, G. A. (2004). Simapro Database Manual - The Franklin US LCI 98 library, Pre Consultants.

Ny, H., MacDonald, J.P., Broman, G., Yamamoto, R., Robert, K.H. (2006). "Sustainability Constraints as System Boundaries." Journal of Industrial Ecology **10**(1-2): 61-77.

NYC New York Housing Maintenance Code - Subchapter 2: Maintenance, Services, and Utilities - Article 3: Painting. New York City Rent Guidelines Board. New York.

O’Connor, J. (2004). Survey on actual service lives for North American buildings. Woodframe Housing Durability and Disaster Issues, Las Vegas, NV.

Optis, M., Wild, P. (2010). "Inadequate documentation in published life cycle energy reports on buildings." The International Journal of Life Cycle Assessment **15**(7): 644-651.

Ortiz, O., Castells, F., Sonnemann, G. (2009). "Sustainability in the construction industry: A review of recent developments based on LCA." Construction and Building Materials **23**(1): 28-39.

Packard, V. (1963). The Waste Makers. London, Penguin.

Palisade (2009). Guide to Using @RISK - Risk Analysis and Simulation Add-In for Microsoft Excel, Version 5.5. Ithaca, NY, Palisade Corporation**:** i-iv.

Patel, M. (2003). "Cumulative energy demand (CED) and cumulative CO_2 emissions for products of the organic chemical industry." Energy **28**(7): 721-740.

Patnaik, A., Satapathy, A., Mahapatra, S.S., Dash, R.R. (2009). "Modeling and Prediction of Erosion Response of Glass Reinforced Polyester-Flyash Composites." Journal of Reinforced Plastics and Composites **28**(5): 513-536.

Paulsen, J. H. (2003). "The Maintenance of Linoleum and PVC Floor Coverings in Sweden." The International Journal of Life Cycle Assessment **8**(6): 357-364.

Pervaiz, M. and M. Sain (2003). "Carbon storage potential in natural fiber composites." Resources Conservation and Recycling **39**(4): 325-340.

Petersen, A. K., Solberg, B. (2004). "Greenhouse Gas Emissions and Costs Over the Life Cycle of Wood and Alternative Flooring Materials." Climatic Change **64**(1-2): 143-167.

PlasticsEurope. (2000). "Plastics Europe Ecoprofiles: Ecoprofiles of Chemicals and Polymers." Retrieved October 1, 2009, from http://www.plasticseurope.org/Content/Default.asp?PageID=1170.

PlasticsEurope (2008). Low Density Polyethylene (LDPE). Environmental Product Declarations of the European Plastics Manufacturers. Brussels, Plastics Europe.

Plat, H. T. (1999). Optimisation of the Life Span of Building Components. 8th International Conference on the Durability of Building Materials and Components, Vancouver, Canada, NRC Research Press.

Pommersheim, J., Clifton, J. (1985). "Prediction of concrete service-life." Materials and Structures **18**(1): 21-30.

Potting, J., Blok, K. (1995). "Life Cycle Assessment of Four Types of Floor Covering." Journal of Cleaner Production **3**(4): 201-213.

Pullen, S. (2000). Energy Assessment of Institutional Buildings. 34th Annual Conference of the Australia & New Zealand Architectural Science Association, Adelaide, Australia

Reap, J., Roman, F., Guldberg, T., Bras, B. (2006). Integrated Ecosystem Landscape and Industrial Modeling for Strategic Environmentally Conscious Process Technology Selection. 13th CIRP INTERNATIONAL CONFERENCE ON LIFE CYCLE ENGINEERING, Leuven, Netherlands.

Rudbeck, C. (1999). Methods for Designing Building Envelope Components Prepared for Repair and Maintenance. Department of Buildings and Energy. Lyngby, Denmark, Technical University of Denmark. **Ph.D.**

Santulli, C. and A. Caruso (2009). "A Comparative Study on Falling Weight Impact Properties of Jute/Epoxy and Hemp/Epoxy Laminates." Malaysian Polymer Journal **4**(1): 19-29.

Scharai-Rad, M., Welling, J. (2002). Environmental and energy balances of wood products and substitutes. Rome, Food and Agriculture Organization of the United Nations.

Scheuer, C., Keoleian, G.A., Reppe, P. (2003). "Life Cycle Energy and Environmental Performance of a New University Building: Modeling Challenges and Design Implications." Energy and Buildings **35**(10): 1049-1064.

Schianetz, K., Kavanagh, L., Lockington, D. (2007). "Concepts and Tools for Comprehensive Sustainability Assessments for Tourism Destinations: A Comparative Review." Journal of Sustanible Tourism **15**(4): 369-389.

Schmehl, M., J. Müssig, et al. (2008). "Life Cycle Assessment on a Bus Body Component Based on Hemp Fiber and PTP®." Journal of Polymers and the Environment **16**(1): 51-60.

Schmidt, A., A. Jensen, et al. (2004). "A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax." The International Journal of Life Cycle Assessment **9**(1): 53-66.

Schmidt, W. and H. Beyer (1998). "Life Cycle Study on a Natural-Fiber-Reinforced Component." SAE transactions **107**(6): 2095-2102.

Seiders, D., Ahluwalia, G., Melman, S., Quint, R., Chaluvadi, A., Liang, M., Silverberg, A., Bechler, C. (2007). Study of Life Expectancy of Home Components. Washington, DC, National Association of Home Builders**:** 1-15.

Sharrard, A. L., Matthews, H.S., Ries, R.J. (2008). "Estimating Construction Project Environmental Effects Using an Input-Output-Based Hybrid Life-Cycle Assessment Model." Journal of Infrastructure Systems **14**(4): 327-336.

Shohet, I. M., Paciuk, M. (2004). "Service life prediction of exterior cladding components under standard conditions." Construction Management and Economics **22**(10): 1081-1090.

Shohet, I. M., Paciuk, M. (2006). "Service life prediction of exterior cladding components under failure conditions." Construction Management and Economics **24**(2): 131-148.

SimaPro. The Netherlands, Product Ecology Consultants (Pre).

Sjostrom, C., Jernberg, P., Caluwaerts, P., Kelly, S., Haagenrud, S., Chevalier, J.L. (2002). Implementation of the European Construction Products Directive via the ISO 15686 Standards. 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia

Sjostrom, C., Jernberg, P., Frohnsdorff, G. (2001). International Standards for Design Life of Constructed Assets. CIB World Building Congress, New Zealand.

Song, Y., J. Youn, et al. (2009). "Life cycle energy analysis of fiber-reinforced composites." Composites Part A **40**(8): 1257-1265.

Soratana, K., Marriott, J. (2010). "Increasing innovation in home energy efficiency: Monte Carlo simulation of potential improvements." Energy and Buildings **42**(6): 828-833.

Strand, S. M., Hovde, P.J. (1999). Use of Service Life Data in LCA of Building Materials. Durability of Building Materials and Components 8, Institute for Research in Construction

Stuart, T., Liu, Q., Hughes, M., McCall, R.D., Sharma, H.S.S., Norton, A. (2006). "Structural biocomposites from flax—Part I: Effect of bio-technical fibre modification on composite properties." Composites: Part A **37**(6): 393-404.

Suh, S., Huppes, G. (2002). "Missing Inventory Estimation Tool Using Extended Input-Output Analysis." The International Journal of Life Cycle Assessment **7**(3): 134-140.

Sullivan, M. I. (2007). Statistics: informed decisions using data, Pearson Prentice Hall.

Suzuki, M., Oka, T. (1998). "Estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan." Energy and Buildings **28**(1): 33-41.

Suzuki, T., Takahashi, J. (2005). Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. 9th Japan International SAMPE Symposium (JISSE-9), Tokyo, Japan.

Tan, R. and A. Culaba (2002). Environmental Life-Cycle Assessment: A Tool for Public and Corporate Policy Development, Manila, De La Salle University**:** 12.

Teixeira, R., Domingis, T. (2006). Computable General Equilibrium Models and the Environment. AERNA 2006. Lisbon, Portugal**:** 1-25.

Thamae, T. (2008). Developing and Characterizing New Materials Based on Natural Fibres and Waste Plastic. Chemical Engineering. Kingston, Ontario, Queen`s University. **Ph.D.:** 258.

Thormark, C. (2002). "A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential." Building and Environment **37**(4): 429-435.

Tripathy, A. (2009). Characterization of Flax Fibres and the Effect of Different Drying Methods for Making Biocomposites. Department of Agricultural and Bioresource Engineering. Saskatoon, Saskatchewan, University of Saskatchewan. **M.S.:** 124.

Udo de Haes, H. A., Heijungs, R. (2007). "Life-cycle assessment for energy analysis and management." Applied Energy **84**(7-8): 817-827.

Udo de Haes, H. A., Heijungs, R., Suh, S., Huppes, G. (2004). "Three Strategies to Overcome the Limitations of Life-Cycle Assessment." Journal of Industrial Ecology **8**(3): 19-32.

Umair, S. (2006). Environmental Impacts of Fiber Composite Materials - Study on Life Cycle Assessment of Materials used for Ship Superstructure. Department of Urban Planning and Environment. Stockholm Royal Institue of Technology. **M.S. :** 63.

USDA. (2010). "National Agricultural Statistics Service." Retrieved February 2011, 2010, from http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/.

van Dam, J. E. G., Bos, H.L. (2004). The Environmental Impact of Fibre Crops in Industrial Applications. Rome, FAO.

van de Velde, K., Kiekens, P. (2001a). "Influence of Fiber Surface Characteristics on the Flax/Polypropylene Interface." Journal of Thermoplastic Composite Materials **14**(3): 244-260.

van de Velde, K., Kiekens, P. (2001b). "Influence of Fibre and Matrix Modifications on Mechanical and Physical Properties of Flax Fibre Reinforced Poly(propylene)." Macromolecular Materials and Engineering **286**(4): 237-242.

van Nes, N., Cramer, J. (2003). "Design strategies for the lifetime optimisation of products." The Journal of Sustainable Product Design **3**(3-4): 101-107.

van Nunen, H., Hendriks, N.A. (2002). A Solution to Environmental Pressure and Housing Convenience. 9th International Conference on Durability of Building Materials and Components (DBMC), Brisbane, Australia

Vink, E., K. Rabago, et al. (2003). "Applications of life cycle assessment to NatureWorksTM polylactide(PLA) production." Polymer Degradation and Stability **80**(3): 403-419.

Wackernagel, M., Onisto, L., Bello, P., Linares, A.C., Falfan, I.S.L., Garcia, J.M., Guerrero, A.I.S., Guerrero, M.G.S. (1999). "National natural capital accounting with the ecological footprint concept." Ecological Economics **29**(3): 375-390.

Wang, M., Wu, Y., Elgowainy, A. (2007). Operating Manual for GREET, Center for Transportation Research Argonne National Laboratory**:** 1-149.

Winistorfer, P., Chen, Z., Lippke, B., Stevens, N. (2005). Energy Consumption and Greenhouse Gas Emissions Related to the Use, Maintenance and Disposal of a Residential Structure. Seattle, WA, Consortium on Research of Renewable Industrial Materials (CORRIM).

Winther, B. N., Hestnes, A.G. (1999). "Solar Versus Green: The Analysis of a Norwegian Row House." Solar Energy **66**(6): 387-393.

Woller, J. (1996). "The Basics of Monte Carlo Simulations." Retrieved December 21, 2010, from http://www.chem.unl.edu/zeng/joy/mclab/mcintro.html.

Wotzel, K., R. Wirth, et al. (1999). "Life cycle studies on hemp fibre reinforced components and ABS for automotive parts." Die Angewandte Makromolekulare Chemie **272**(1): 121-127.